From black holes to the Universe Part 3:

… the stuff in between everything else

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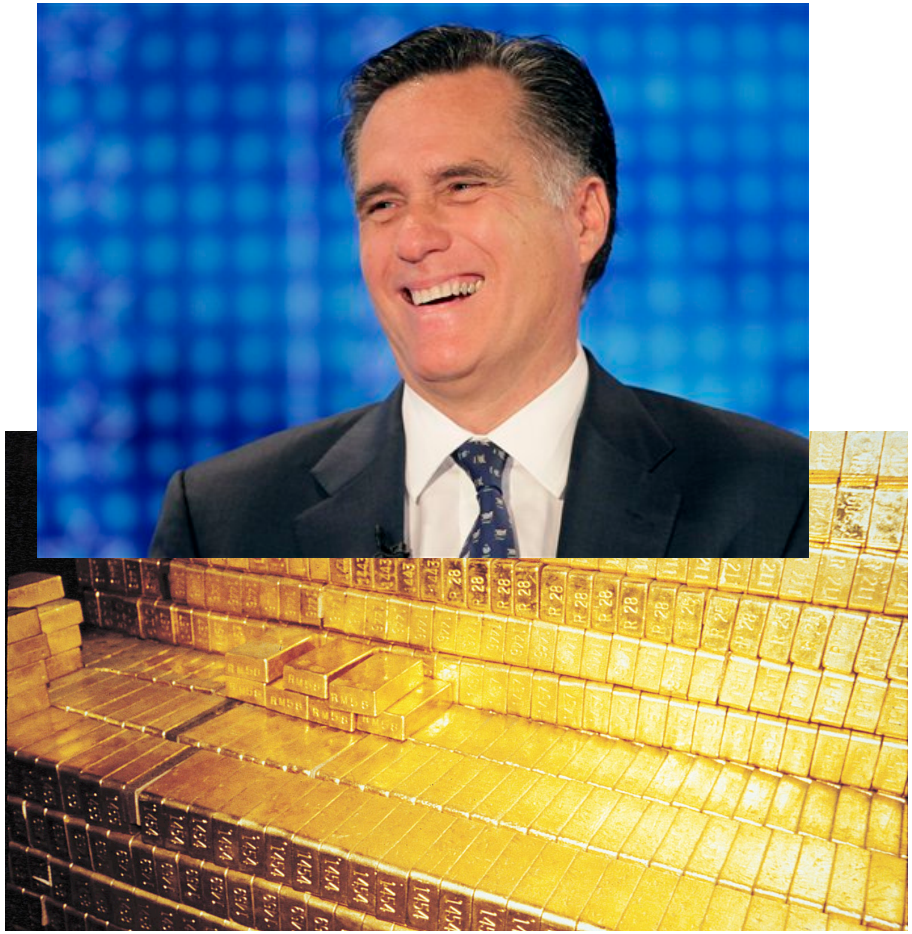
+ T. Di Matteo + N. Khandai + V. Springel

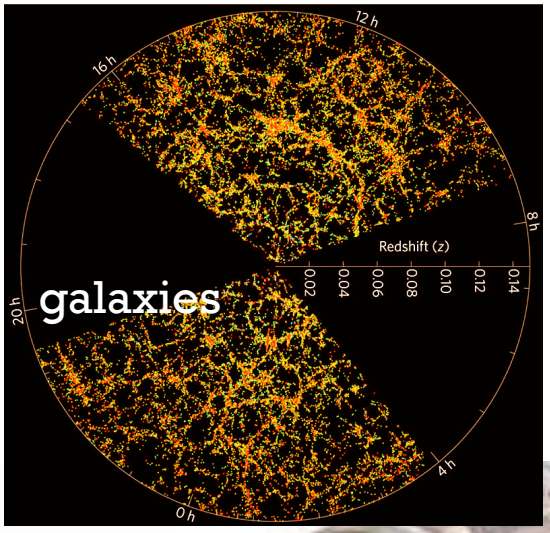
USED CARS

Which dataset

…. will contain a quarter of a billion pixels of 3D cosmological information?



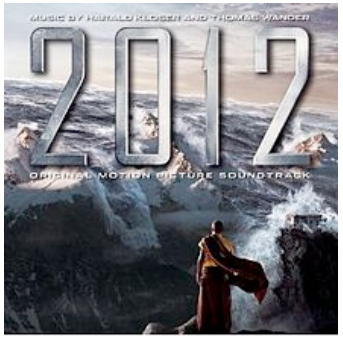
quarter of a billion



million

Which dataset

…. is minimally contaminated by pollution from galaxy formation?

Which dataset (July 

)

…. will be public in 6 months?

Plan:

- History : -the first quasar spectra and first Lya forest
  -first theoretical models (all wrong)
  -CDM cosmology meets the Lya forest

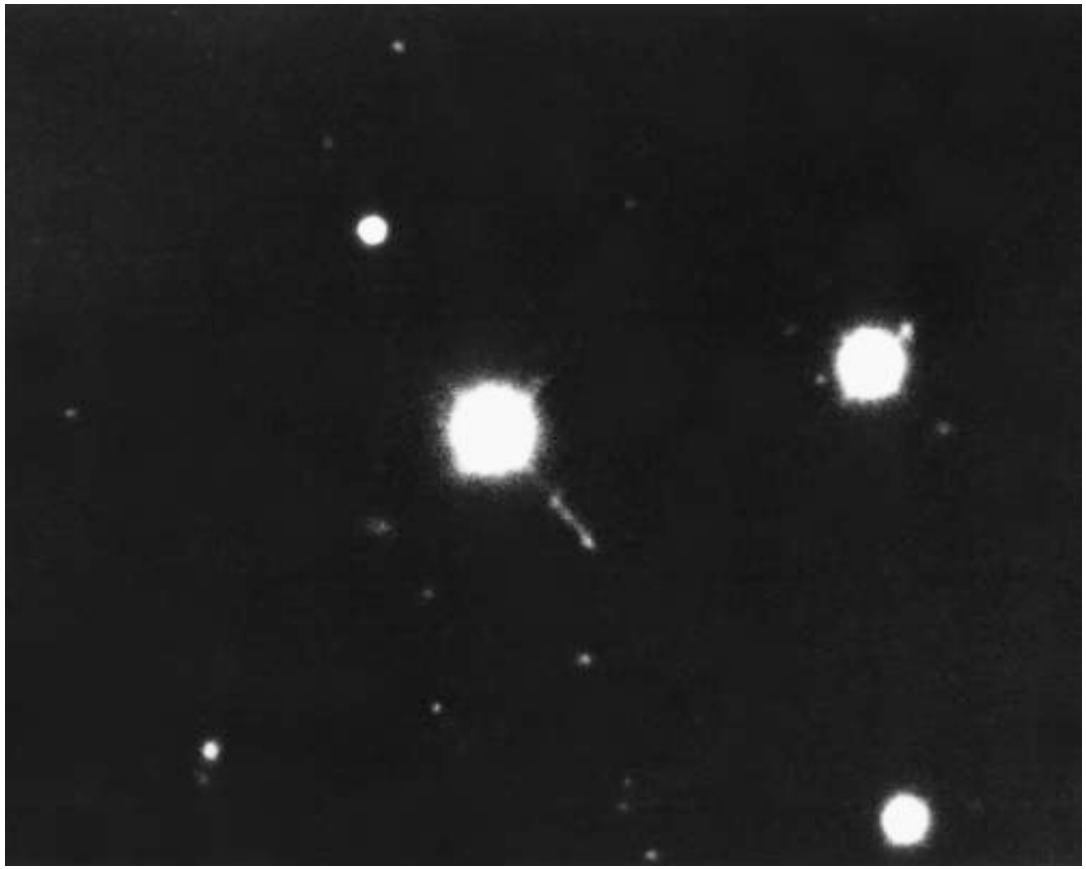
- The intergalactic medium in simulations

- New data from SDSS/BOSS

- The Lya forest as cosmological tool:

  -the matter power spectrum
  -constraints on neutrino mass
  -baryon oscillations

- Conclusions



First optically identified quasar (Maarten Schmidt 1965)

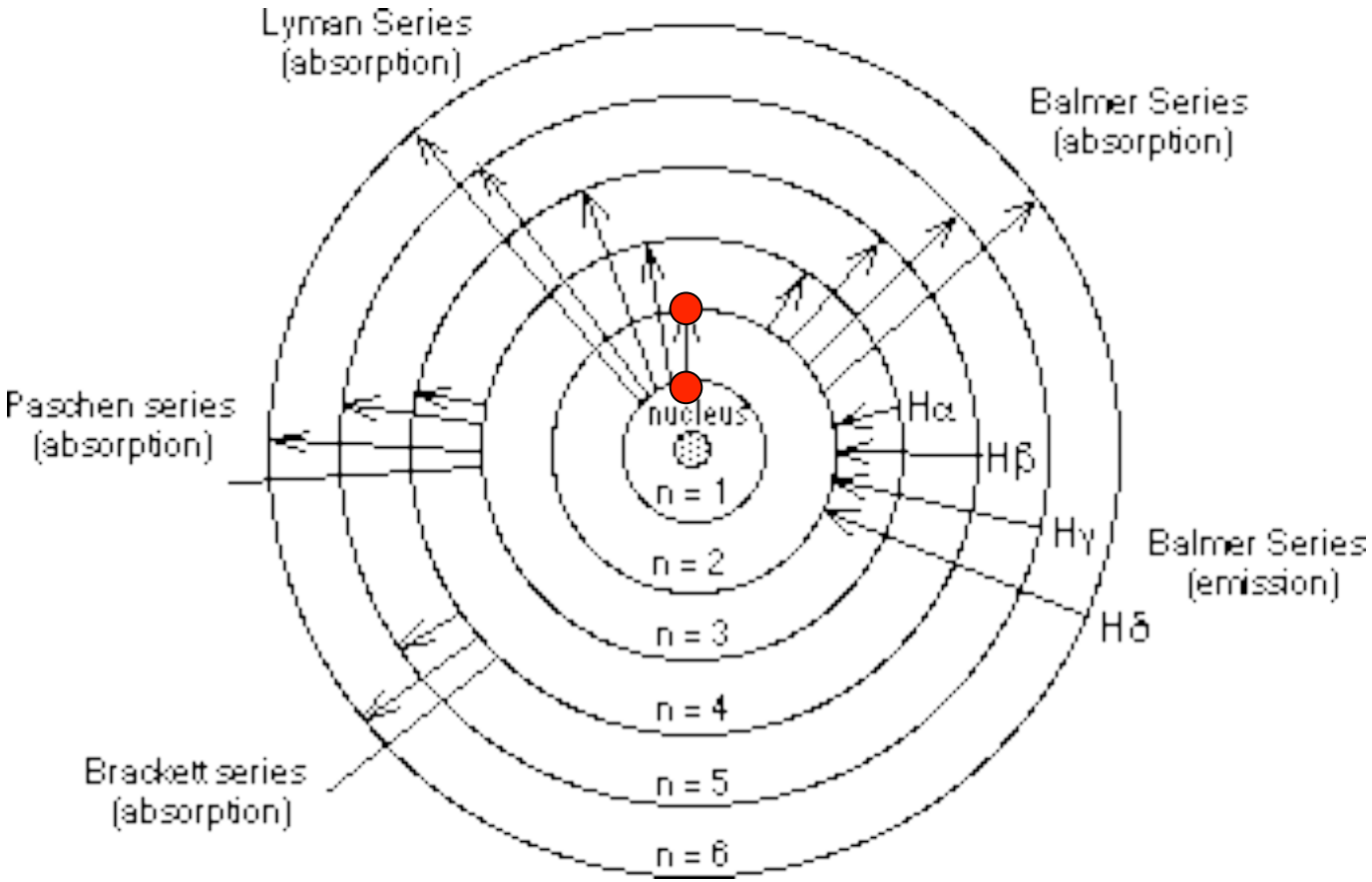
Gunn and Peterson (1965)

NOTES

ON THE DENSITY OF NEUTRAL HYDROGEN IN INTERGALACTIC SPACE

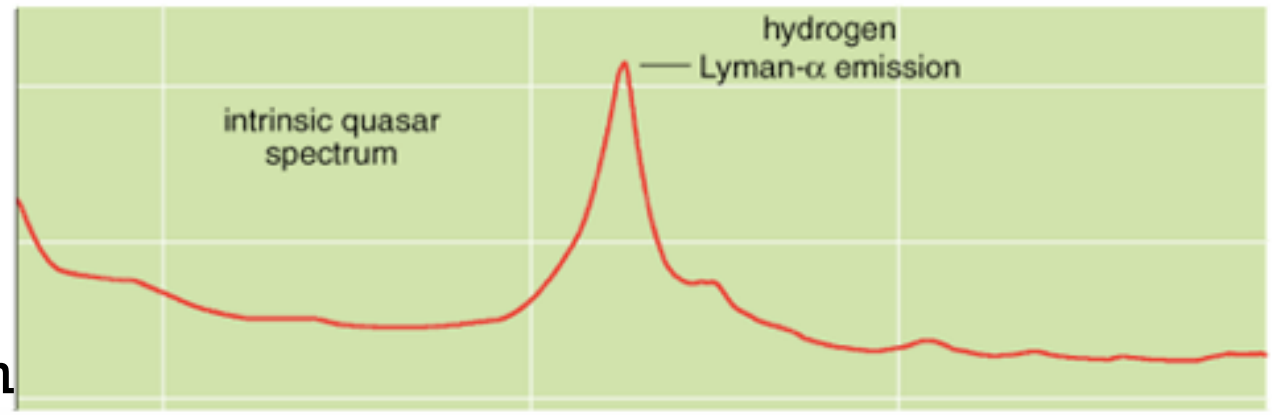
Recent spectroscopic observations by Schmidt (1965) of the quasi-stellar source 3C 9, which is reported by him to have a redshift of 2.01, and for which Lyman-α is in the visible spectrum, make possible the determination of a new very low value for the density of neutral hydrogen in intergalactic space. It is observed that the continuum of the source continues (though perhaps somewhat weakened) to the blue of Ly-α; the line as seen on the plates has some structure but no obvious asymmetry. Consider, however, the fate of photons emitted to the blue of Ly-α. As we move away from the source along the line of sight, the source becomes redshifted to observers locally at rest in the expansion, and for one such observer, the frequency of any such photon coincides with the rest frequency of Ly-α in his frame and can be scattered by neutral hydrogen in his vicinity. The calculation of the size of the effect is very easily performed as follows:

$$\tau = \left[\frac{\pi e^2}{m_e c} f_\alpha \lambda_\alpha\right] H^{-1}(z) n_{\mathrm{HI}}(z)$$



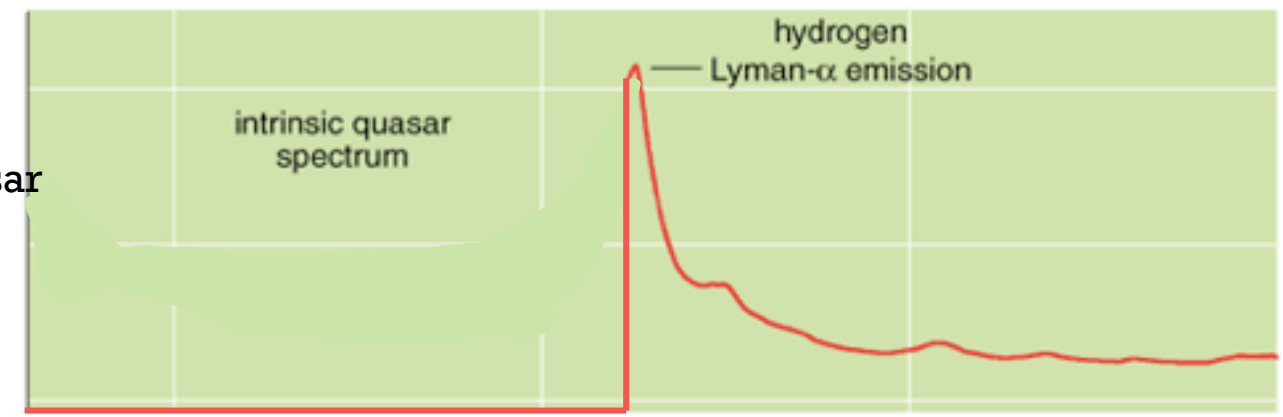
Energy levels of a Hydrogen atom

We are interested in the transmitted flux, F:



wavelength →

$$F = \frac{F_{\text{observed}}}{F_{\text{intrinsic quasar spectrum}}}$$



$$F = e^{-\tau}$$

$$\tau = \left[\frac{\pi e^2}{m_e c} f_\alpha \lambda_\alpha\right] H^{-1}(z) n_{\mathrm{HI}}(z)$$

for H at mean density, of the Universe $\tau = 10^6$!

Bahcall and Salpeter (1965)

ON THE INTERACTION OF RADIATION FROM DISTANT SOURCES WITH THE INTERVENING MEDIUM

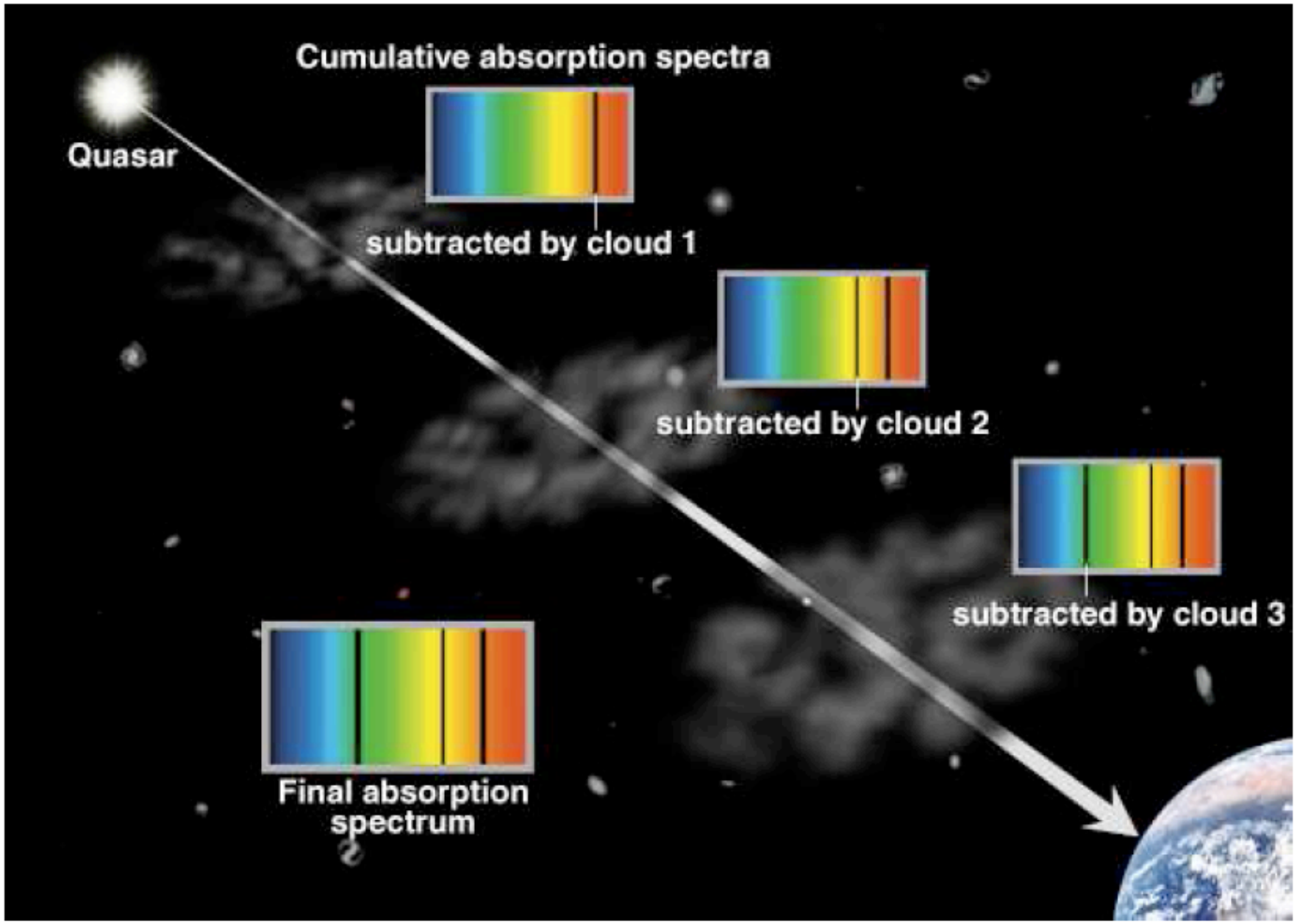
We discuss several ways that a distant radiation source (with a large redshift assumed due to the cosmological expansion) can provide information over a wide range of distances about the intervening medium. As we shall show [cf. Gunn and Peterson (1965)] neutral hydrogen (or other atoms) at various distances between the source and us will give rise to an "absorption trough" in the continuous spectrum of a distant source. If the neutral hydrogen is instead concentrated in clusters of galaxies, this trough is replaced by a number of sharp absorption lines. Besides discussing (i) absorption troughs and (ii) absorption lines from clusters, we also consider (iii) photon scattering by free electrons in the intervening medium and (iv) spreading of a radio beam due to inhomogeneities in the ionized gas that is traversed. Present observations furnish some stringent upper limits, and we suggest other feasible cosmological tests.

Let $z \equiv (\Delta\lambda/\lambda)$ be the "distance" or redshift measure, q_0 the deceleration parameter for the usual cosmological models (with cosmological constant equal to zero) that satisfy the field equations of general relativity (see, e.g., Bondi 1961, or Sandage 1961*a*, *b*), H the Hubble parameter with $H_0 \approx (10^{+10}\text{ years})^{-1}$ (a subscript zero indicates a local value at the present epoch), and N the total density (in nucleons per cm^3). The evolving cosmologies[1] require that the *total* number density satisfy a relation of the form:

$$N(z) = (1 + z)^3 N_0 , \tag{1}$$

where $N_0 = 2 \times 10^{-5}\, q_0\ \text{cm}^{-3}$. The steady-state model requires $N(z) \equiv N_0$ with $N_0 \approx (1 \text{ or } 2) \times 10^{-5}\ \text{cm}^{-3}$ in some versions (Hoyle 1948; Hoyle and Narlikar 1962). We denote the redshift of a distant source by z_s and that of an absorbing layer by z_a.

One can easily estimate (assuming a fairly flat ultraviolet spectrum [Greenstein and Schmidt 1964; Oke 1965; but see also Greenstein 1964]) values of z_s that may be observed in QSS's in the near future. A QSS with the intrinsic brightness of 3C 273 (one of the


Cumulative absorption spectra
Quasar
subtracted by cloud 1
subtracted by cloud 2
subtracted by cloud 3
Final absorption spectrum

First published high-z QSO spectrum: Lynds and Stockton (1966)

THE LARGE REDSHIFT OF THE QUASI-STELLAR SOURCE 1116+12*

A spectrogram of the quasi-stellar source 1116+12 (Bolton, Clarke, Sandage, and Véron 1965) has been obtained with the image-tube Cassegrain spectrograph of the Kitt Peak 84-inch telescope. The instrumentation is essentially the same as that described in an earlier paper (Lynds, Stockton, and Livingston 1965), with the exception that the performance in the ultraviolet has been improved. Wavelength measurements have been made with a Grant photoelectric scanning comparator.

TABLE 1

LINE IDENTIFICATIONS AND COMPUTED REST WAVELENGTHS

Measured λ (Å)	Identification	λ_0 (Å)	Computed λ_0 (Å)*
3372	N II	1085	1082
3792	H(Ly-α)	1216	1217
4830	C IV	1549	1550
5109	He II	1640	1639
5947	C III	1909	1908

* The adopted redshift is $z = 2.117$

The spectrum of 1116+12 is reproduced in Figure 1. The most obvious features in the spectrum are two strong emission lines at 3792 and 4830 Å. These lines are most reasonably identified as Ly-α and C IV λ 1549 with an indicated redshift $z = 2.117$. Both lines are about 20 Å in width. Other emission lines which appear to be present with reasonable

First published high-z QSO spectrum: Lynds and Stockton (1966)

Lya forest

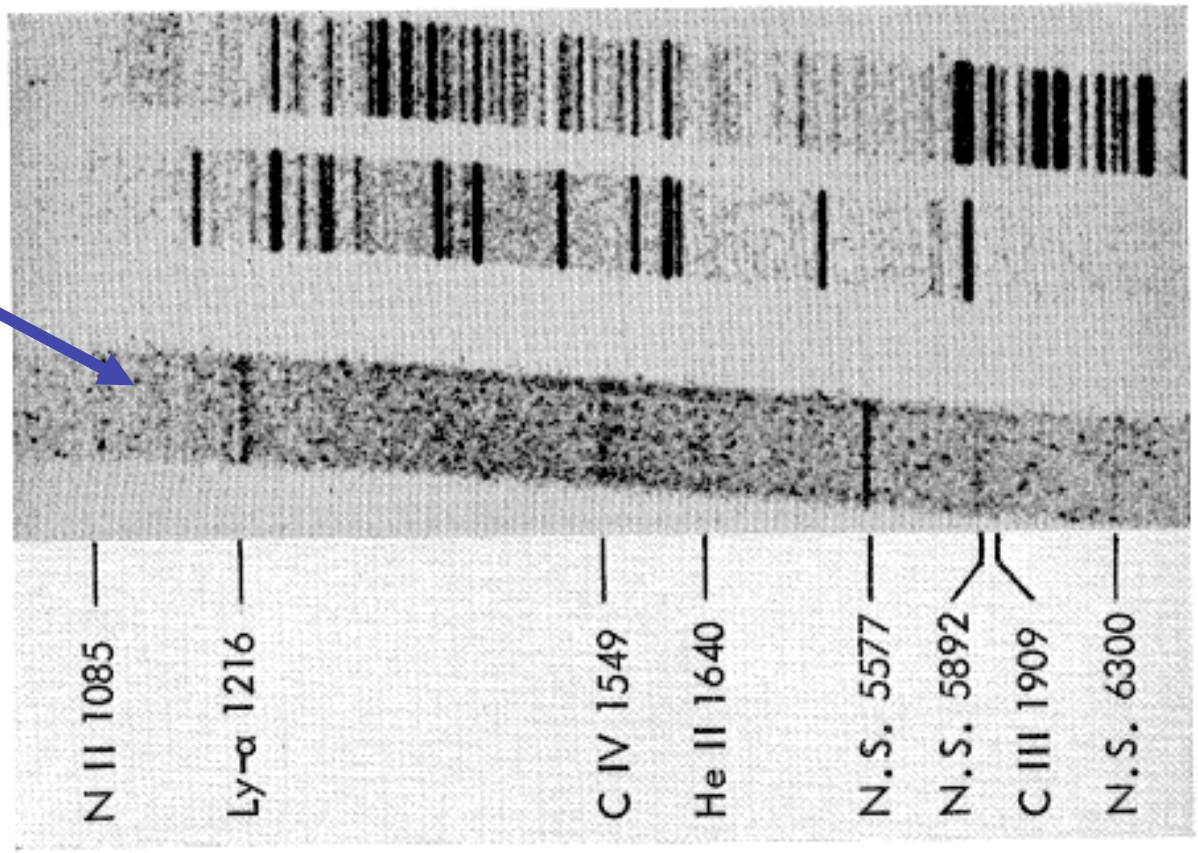
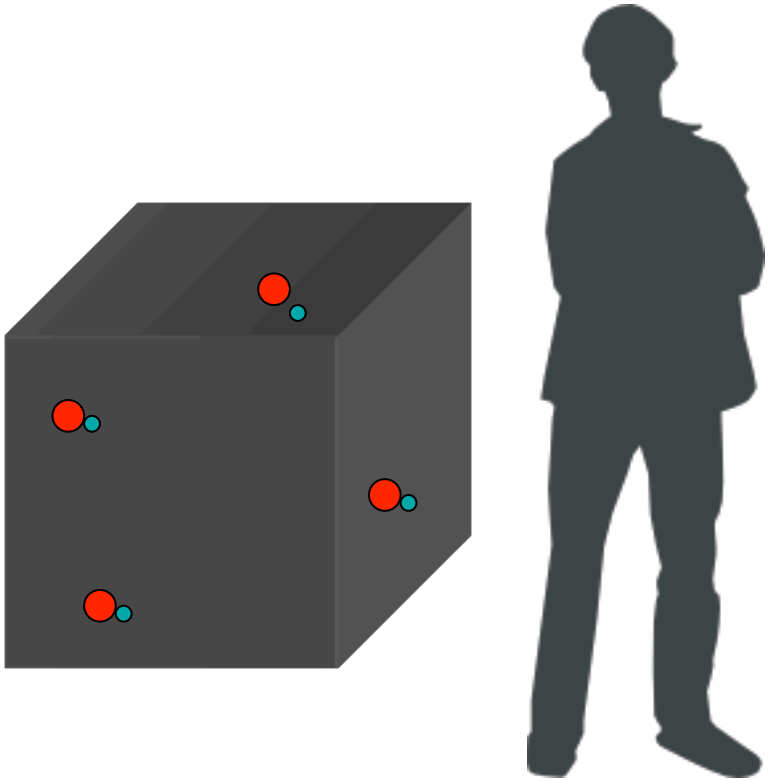


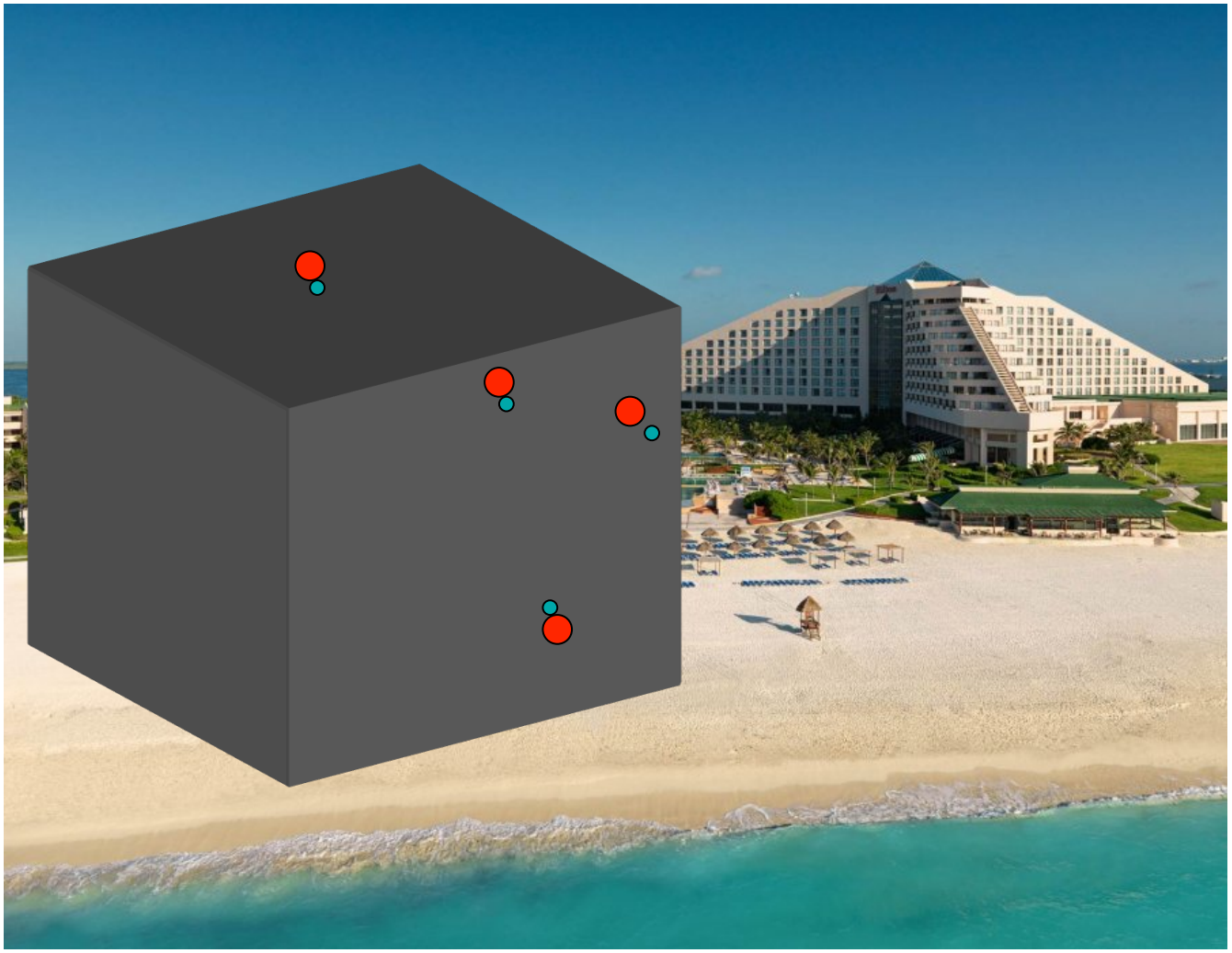
FIG. 1.—The spectrum of the quasi-stellar source 1116 + 12 The upper two spectra are due to the comparison sources: He + Ar + Ne (*top*) and He + Hg + Ar (*center*).

What is the mean density of baryons?

It is less than 4 particles per cubic meter.



but from the absorption seen in spectra, the number density of neutral H atoms is 10^6 times less!



Why? We think the Hydrogen is still there, but it is 99.9999% ionized.

How do we detect these neutral atoms?

First published high-z QSO spectrum: Lynds and Stockton (1966)

Lya forest

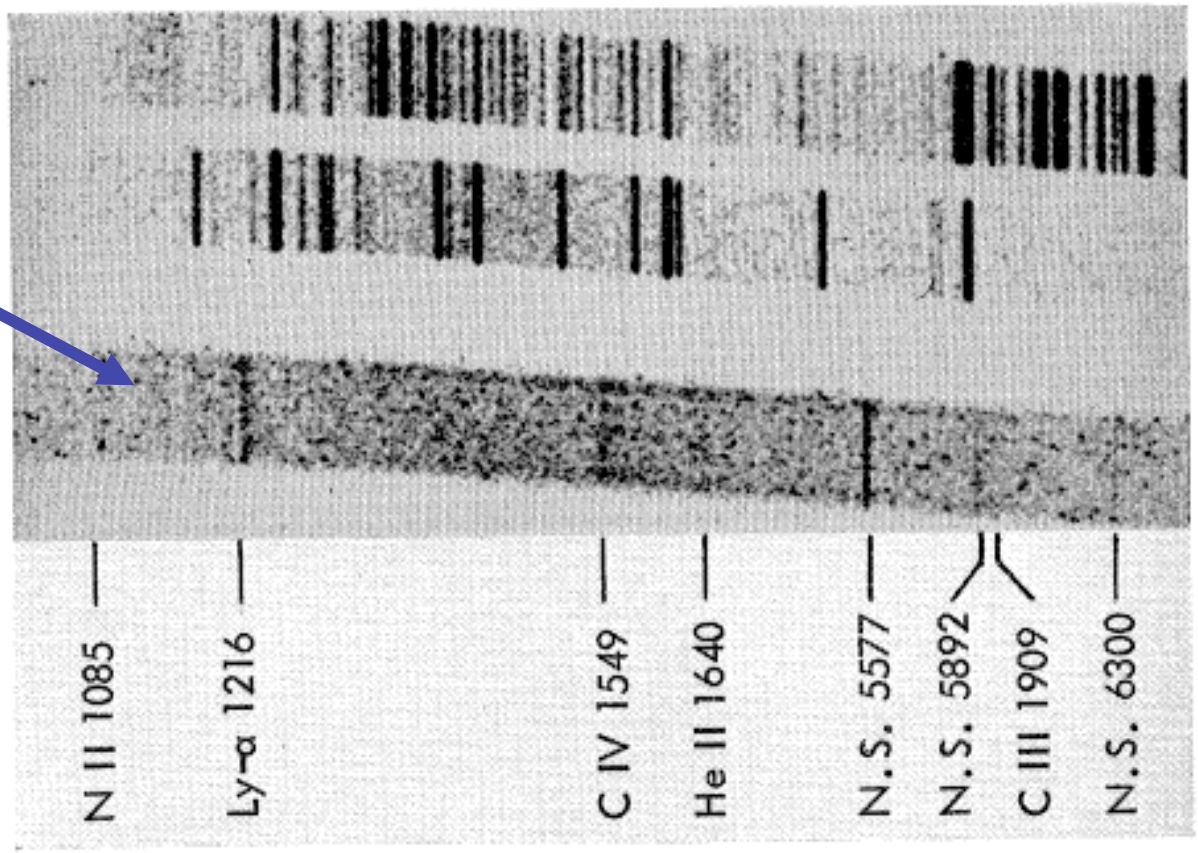
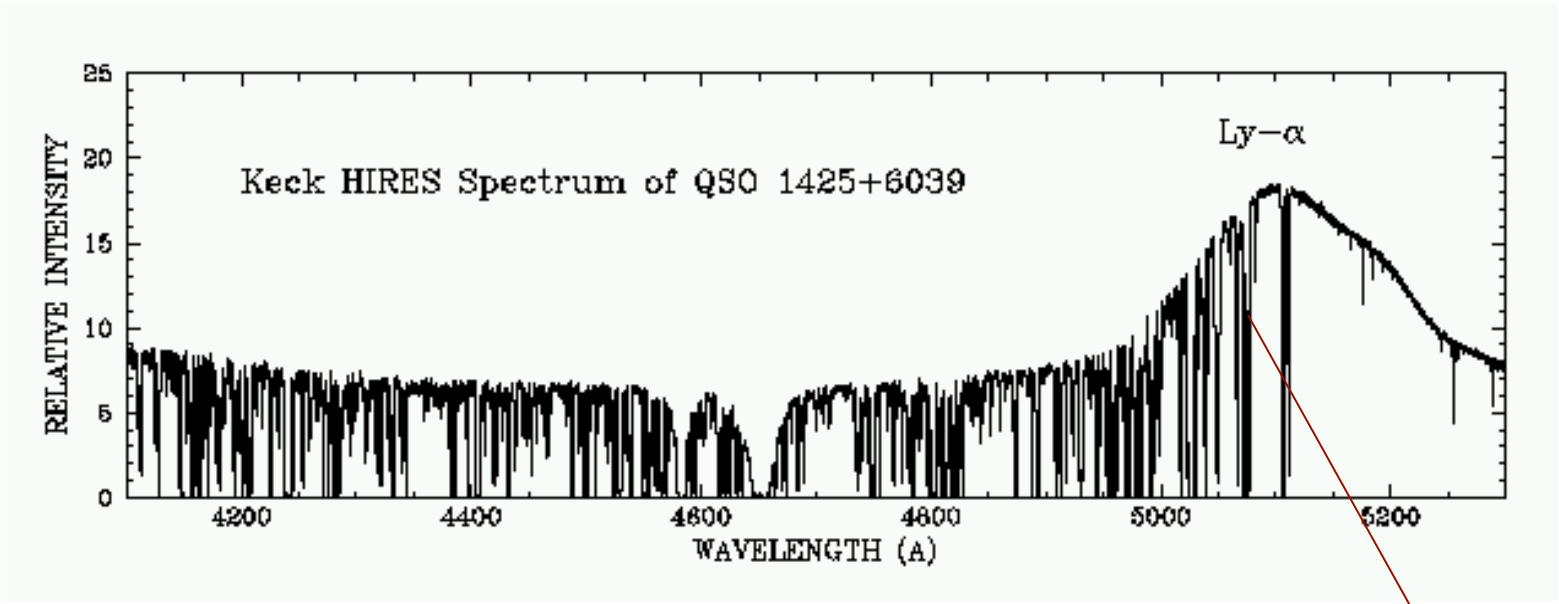


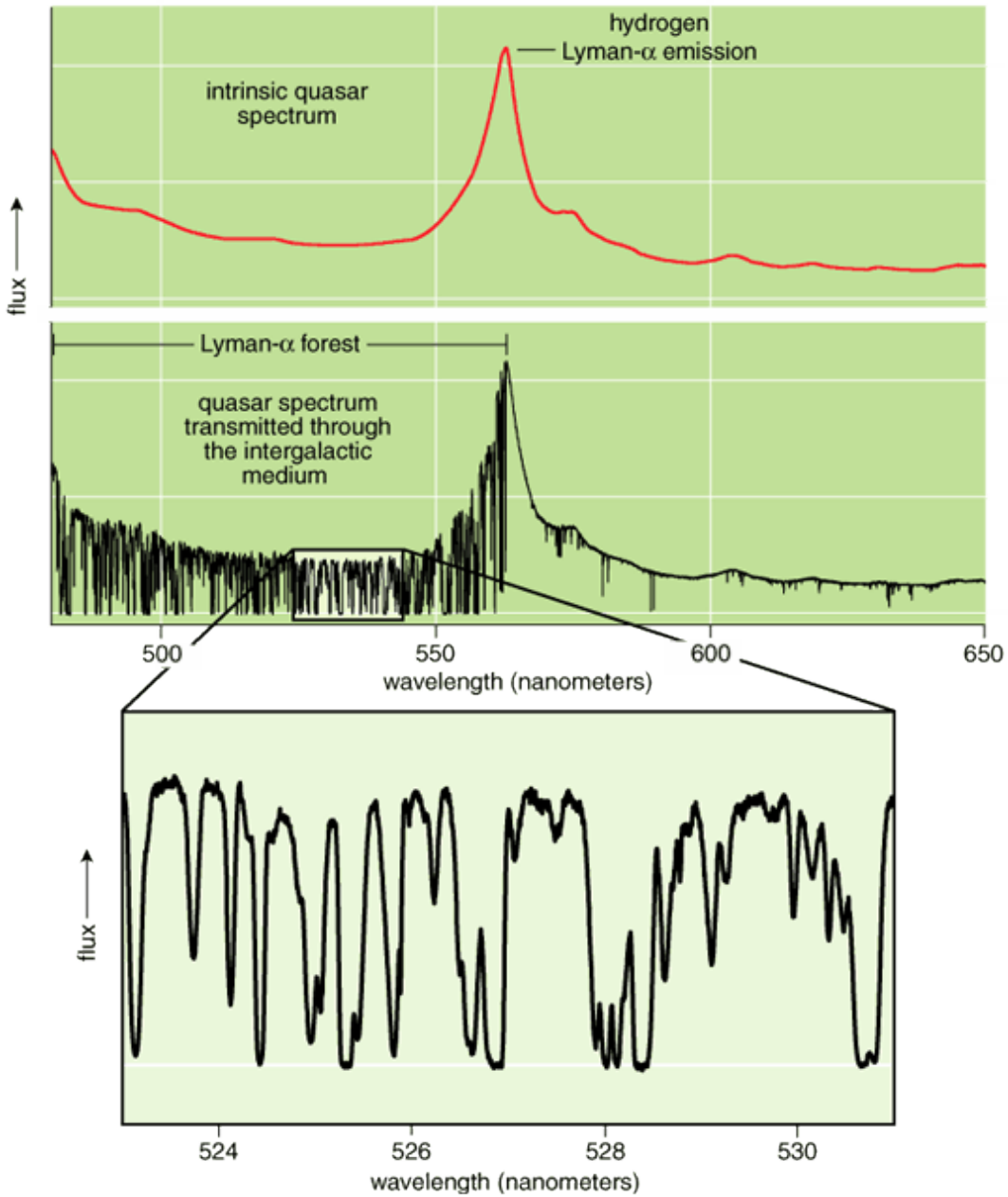
FIG. 1.—The spectrum of the quasi-stellar source 1116 + 12 The upper two spectra are due to the comparison sources: He + Ar + Ne (*top*) and He + Hg + Ar (*center*).

- If we take a spectrum of a quasar, we can see material in absorption:



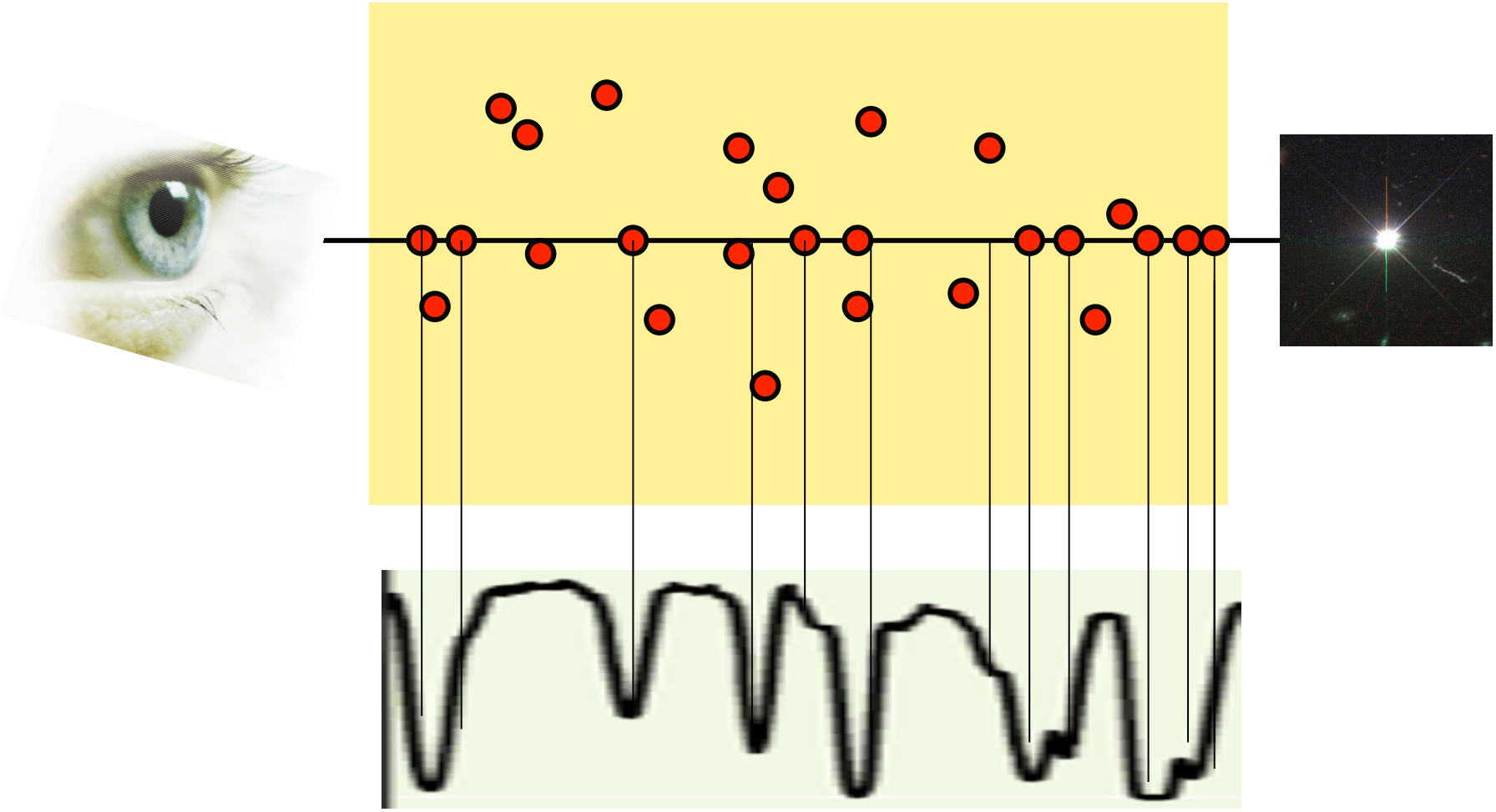
- Light travelling to us from the quasar gets redshifted by the expansion. When the wavelength of light gets to the Lyman-alpha wavelength, there is a probability that a photon will be absorbed by neutral hydrogen gas at that redshift.

Ly-alpha emission line at quasar redshift


hydrogen
Lyman-α emission
intrinsic quasar
spectrum
flux
Lyman-α forest
quasar spectrum
transmitted through
the intergalactic
medium
500
550
600
650
wavelength (nanometers)
flux
524
526
528
530
wavelength (nanometers)

What is the physical interpretation of the absorption features we see?

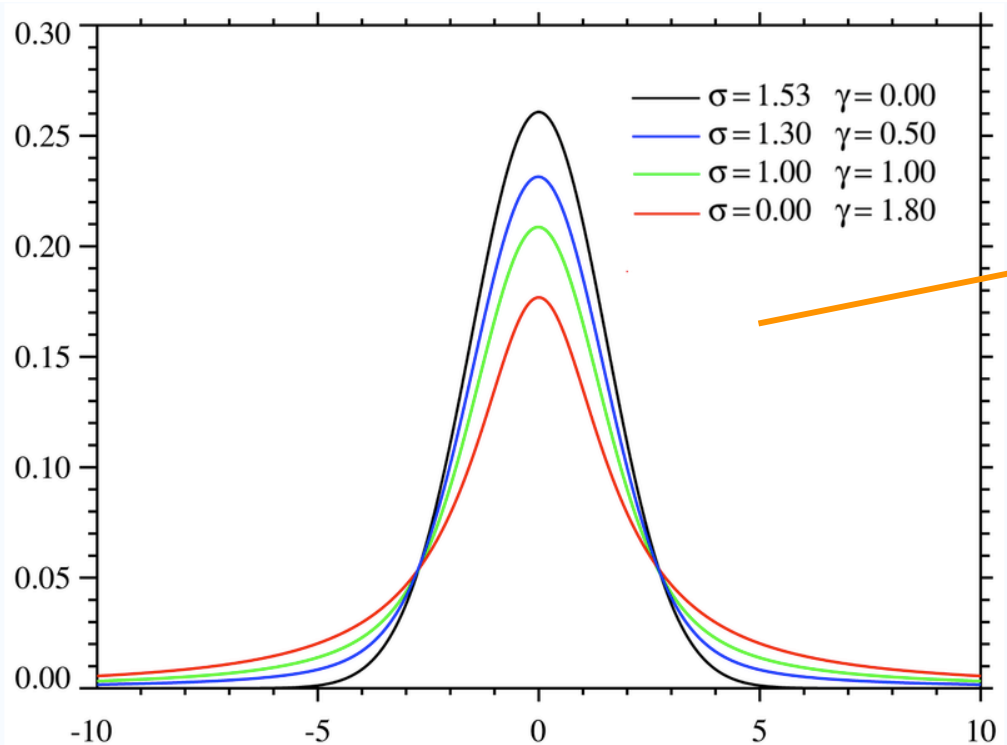
(1966-1994) The original picture:
discrete small clouds + intercloud medium



The width of the clouds in this original model is set by thermal (Doppler) broadening and the intrinsic width (Lorentzian) because the clouds are physically very small in this model

$$V(x;\sigma,\gamma) = \int_{-\infty}^{\infty} G(x';\sigma)L(x-x';\gamma)\,dx'$$

$$G(x;\sigma) \equiv \frac{e^{-x^2/(2\sigma^2)}}{\sigma\sqrt{2\pi}} \qquad L(x;\gamma) \equiv \frac{\gamma}{\pi(x^2+\gamma^2)}.$$

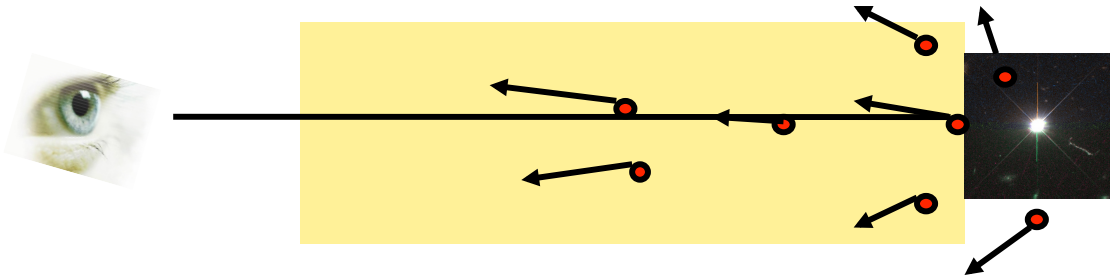


Do these small clouds really exist?

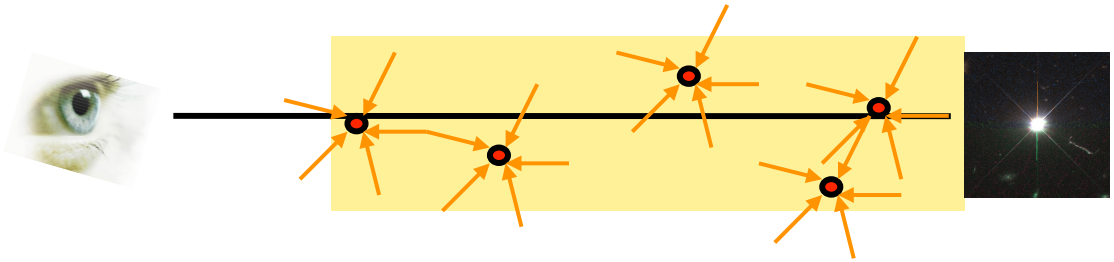
What are they physically?

People tried to explain ….

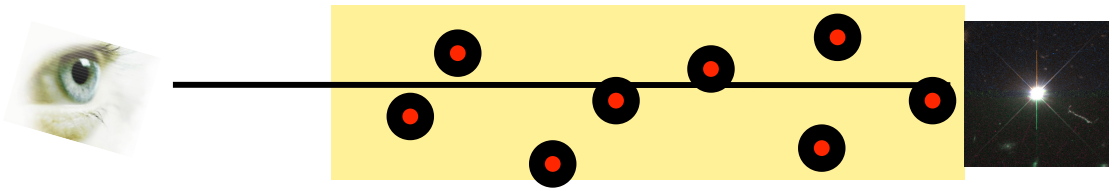
Failed models



Ejected from host QSOs



Pressure confined clouds



Dark matter confined clouds (minihalos)

The correct model:

A fluctuating low density photoionized medium

- absorption is caused by structures which have not yet undergone gravitational collapse

- broadening is done by Hubble flow

How did we find this out?

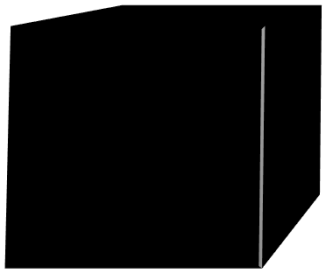
First models by Bi (1991), Bi Ge & Fang (1992) using linear theory. But did not gain wide acceptance until advent of numerical simulations.

e.g. Cen et al (1994), Hernquist et al (1996)

Cosmological N-body simulations

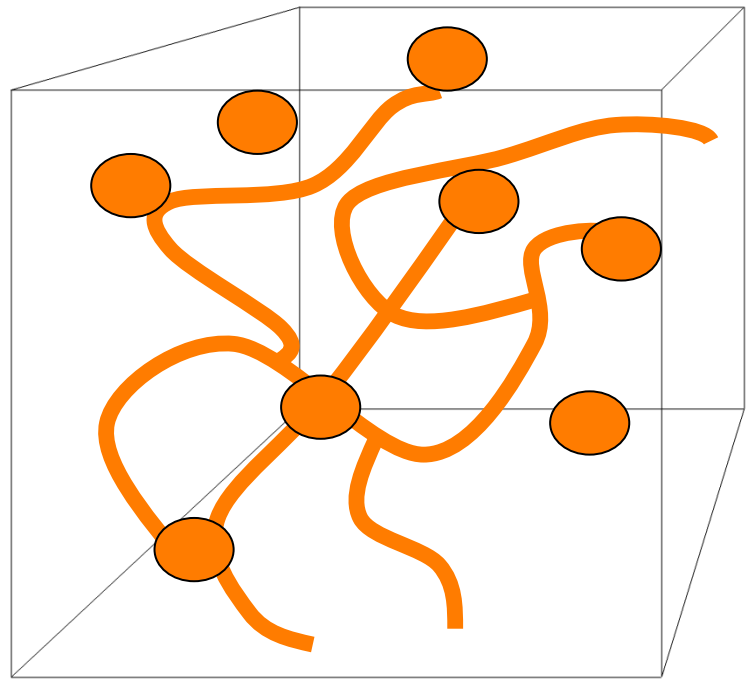
	WMAP
A	0.9 ± 0.1
n_s	0.99 ± 0.04
τ	$0.166^{+0.076}_{-0.071}$
h	0.72 ± 0.05
$\Omega_m h^2$	0.14 ± 0.02
$\Omega_b h^2$	0.024 ± 0.001

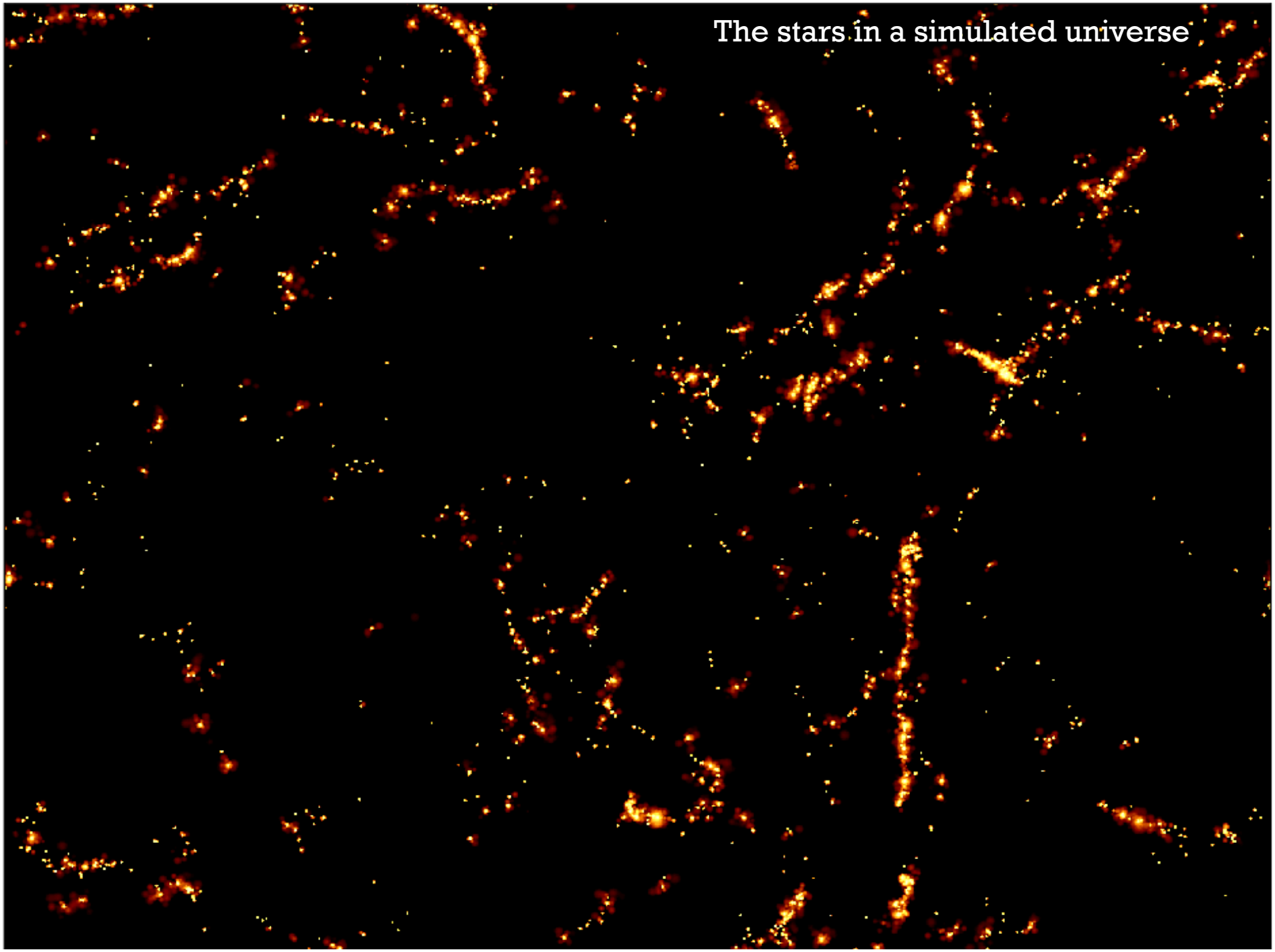
input parameters
for inflationary CDM
model

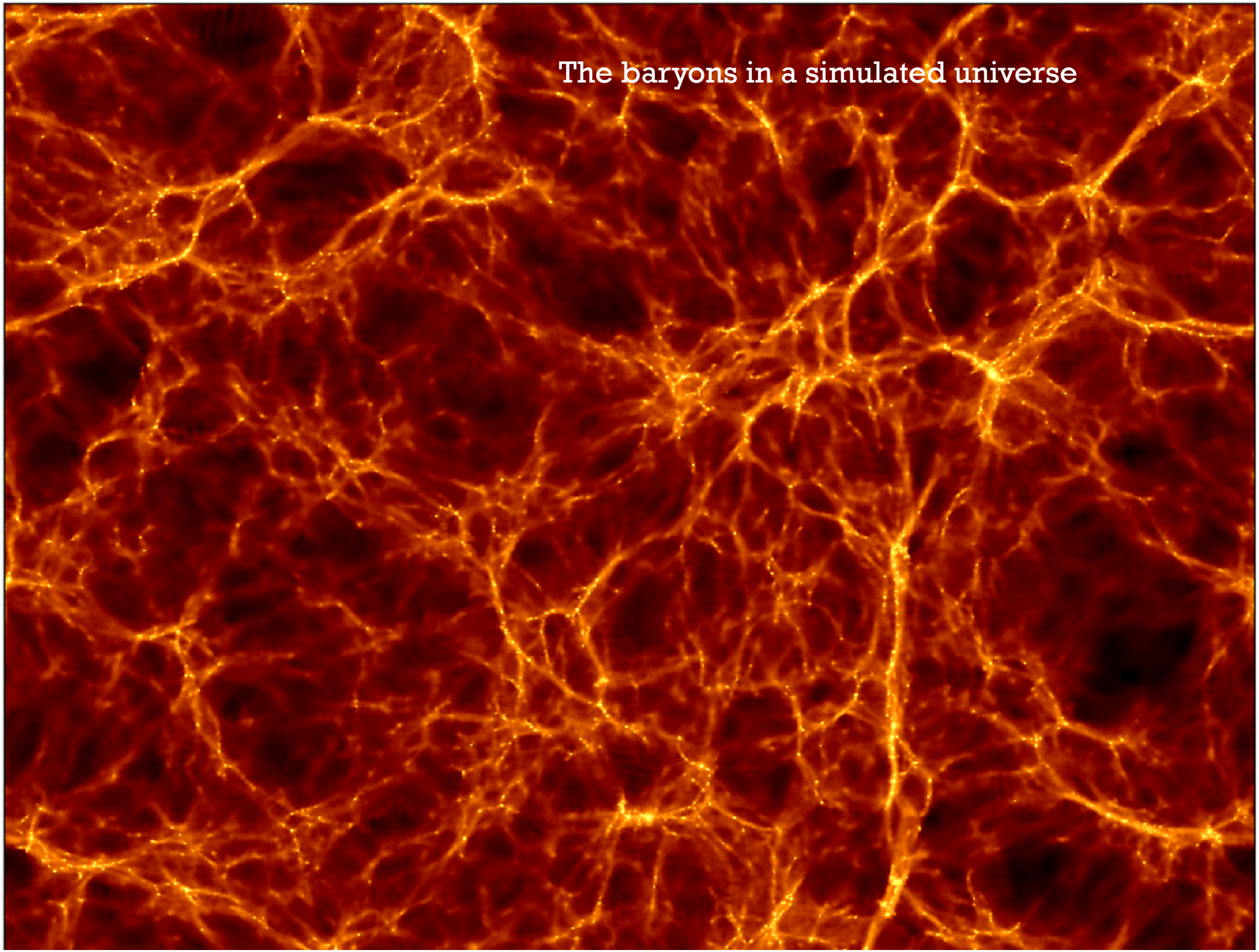


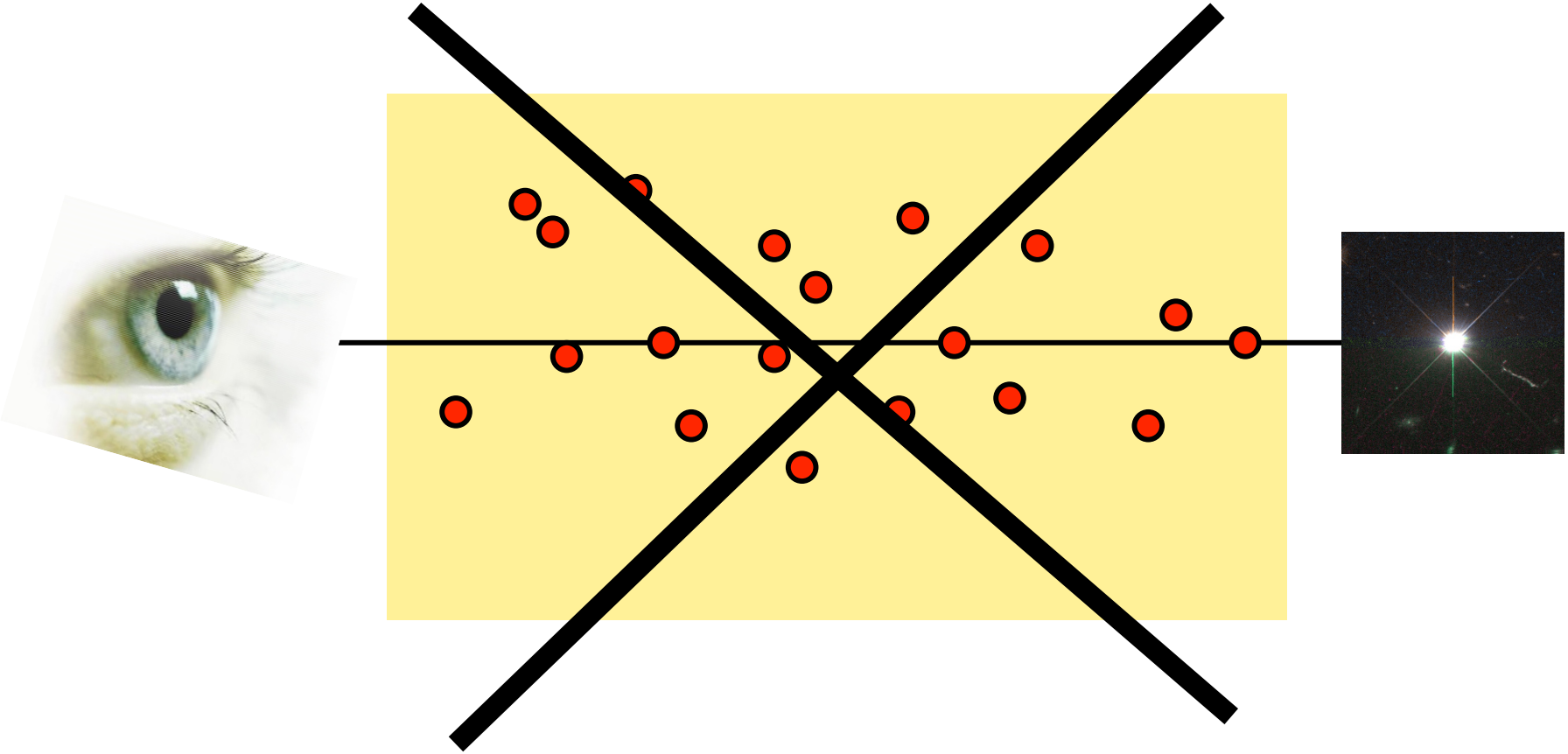
Petagadget

gravity
gas dynamics
gas cooling
star formation algorithms

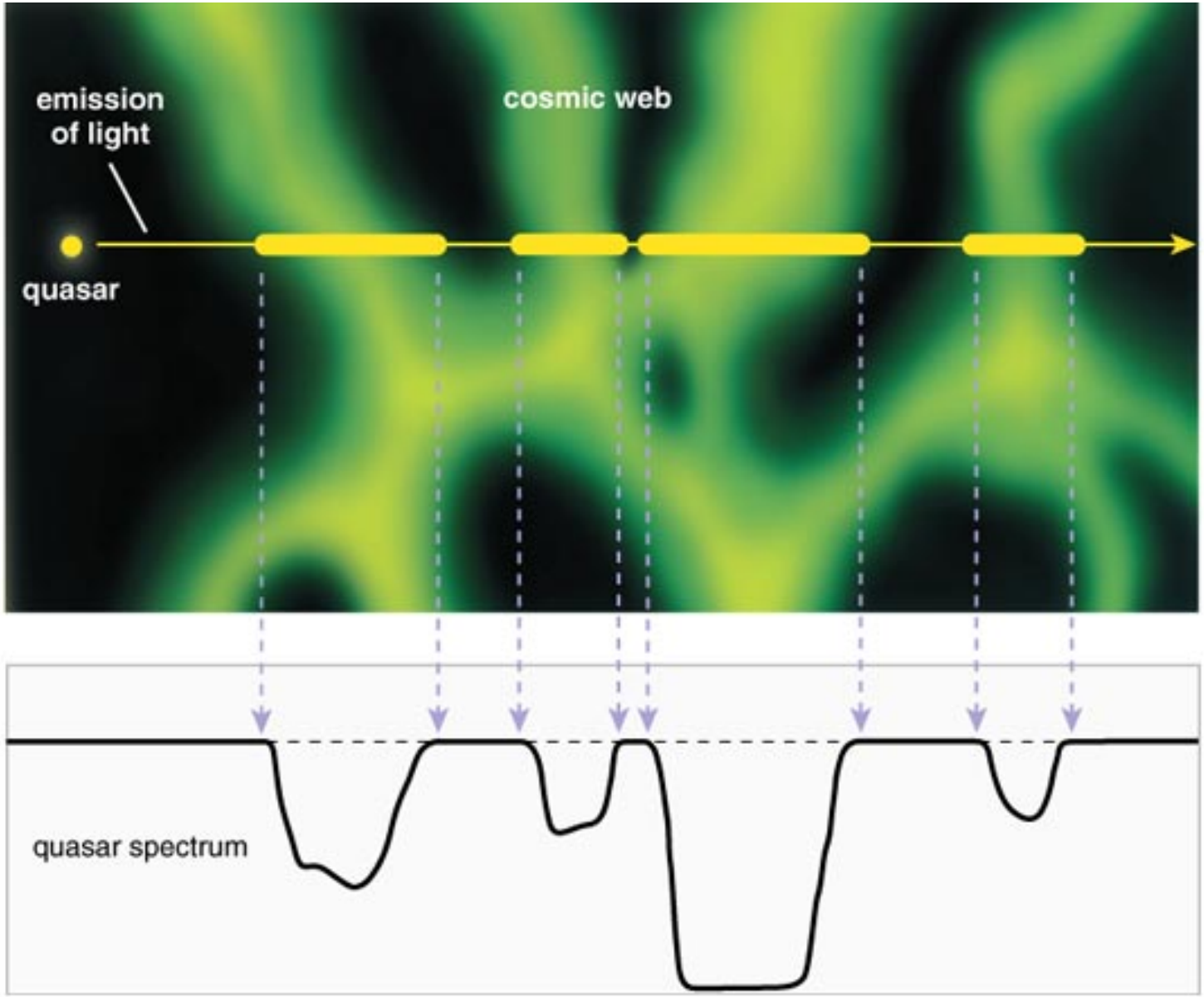



The stars in a simulated universe

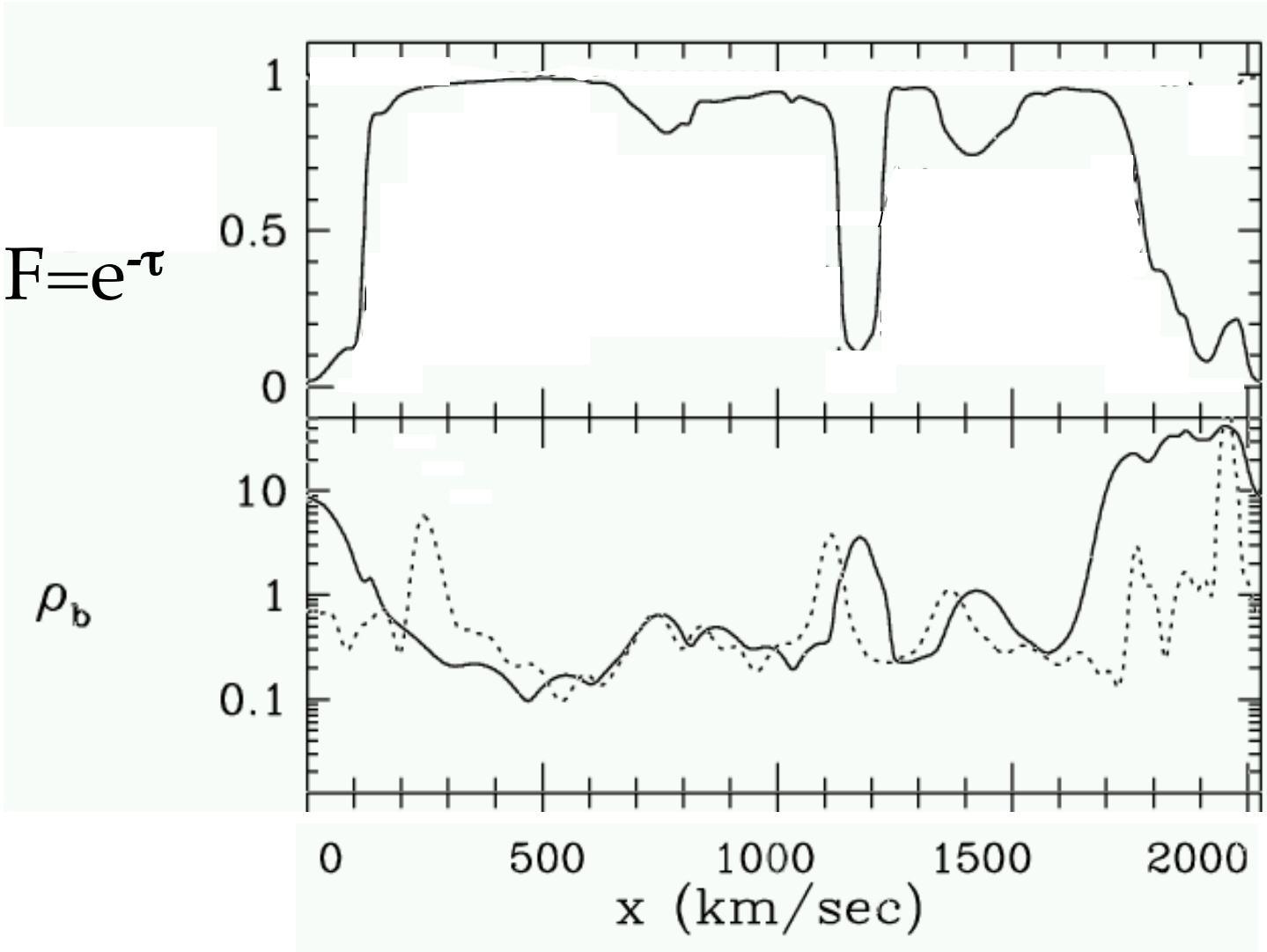

The baryons in a simulated universe



There is no intercloud medium
-the clouds <u>are</u> the medium

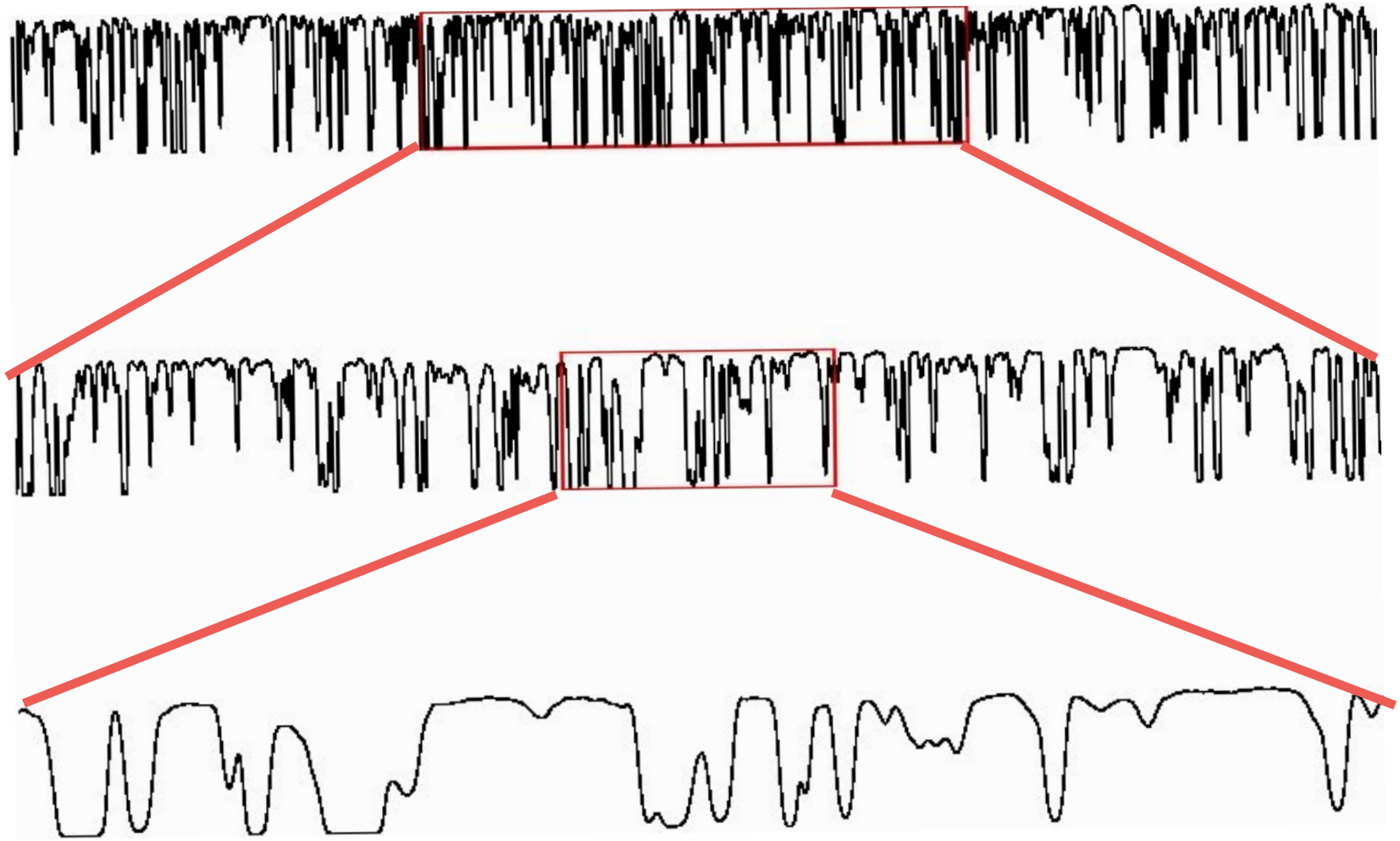

emission
of light
cosmic web
quasar
quasar spectrum

Simulated spectrum of background quasar.

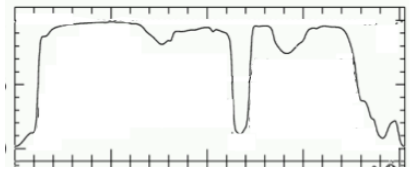


This Lyman-alpha "forest" can give us a 1D map of the density field.

2012 simulations: 132 billion particle Gadget SPH



Khandai, RC & Di Matteo



(1998)

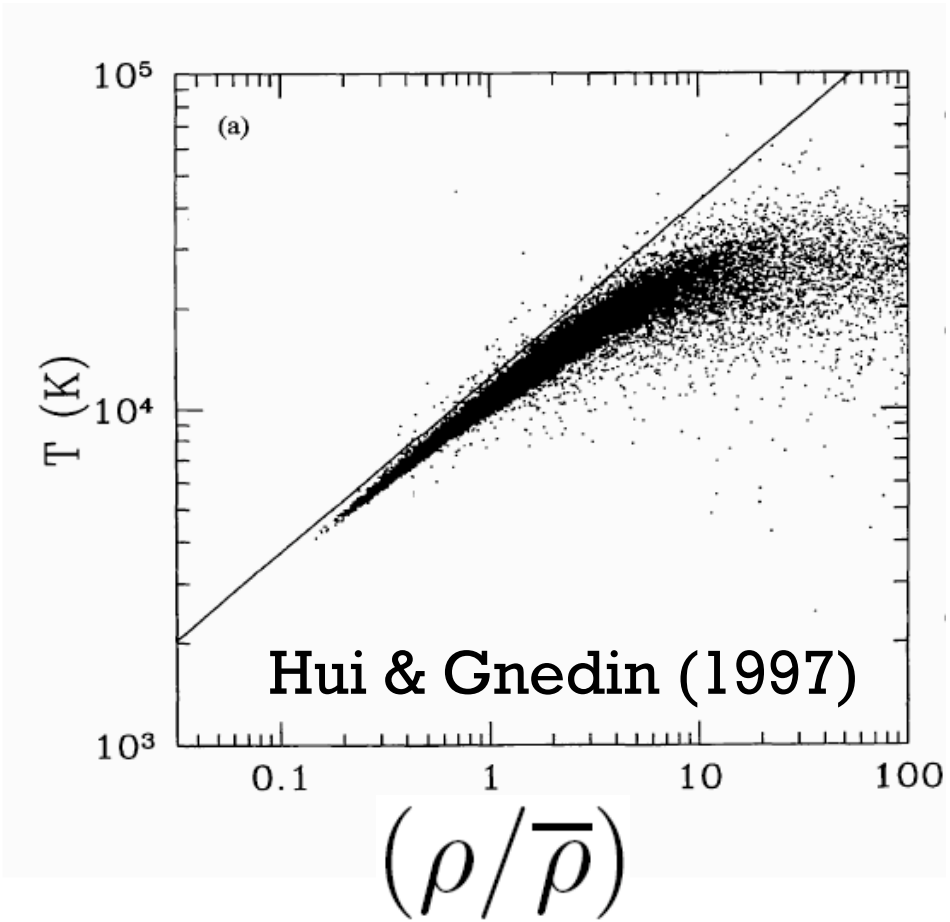
Baryons trace dark matter well on scales above the pressure smoothing scale, ~100 kpc/h

→ if we understand how the baryons are distributed, we can measure the clustering properties of the dark matter from the Lya forest.

What is the physics involved?

Competition between

photoionization heating ⟷ adiabatic cooling from the expansion of the Universe



drives gas elements onto a power-law temperature relation

$$T = T_0(\rho/\overline{\rho})^\gamma$$

$\gamma \sim 0.6$

For the gas in photoionization equilibrium,

$$n_{\rm HI} \propto \rho^2 T^{-0.7}/\Gamma$$

photo ionization rate

(The recombination rate for gas at these temperatures is proportional to $T^{-0.7}$)

We already know that $T = T_0(\rho/\overline{\rho})^\gamma$ the neutral hydrogen density and hence optical depth τ:

$$\tau \propto \rho_b^2 T^{-0.7} = A(\rho_b/\overline{\rho}_b)^\beta,$$

$$A = 0.946\left(\frac{1+z}{4}\right)^6\left(\frac{\Omega_b h^2}{0.0125}\right)^2\left(\frac{T_0}{10^4\ {\rm K}}\right)^{-0.7}\left(\frac{\Gamma}{10^{-12}\ {\rm s}^{-1}}\right)^{-1}\left(\frac{H(z)}{100\ \ {\rm km\ s^{-1}\ Mpc^{-1}}}\right)^{-1}$$

(known as the FGPA, Fluctuating Gunn-Peterson Approximation)

or more simply,

Density of matter

$$\tau \propto \rho^{\sim 1.6}$$

remember that

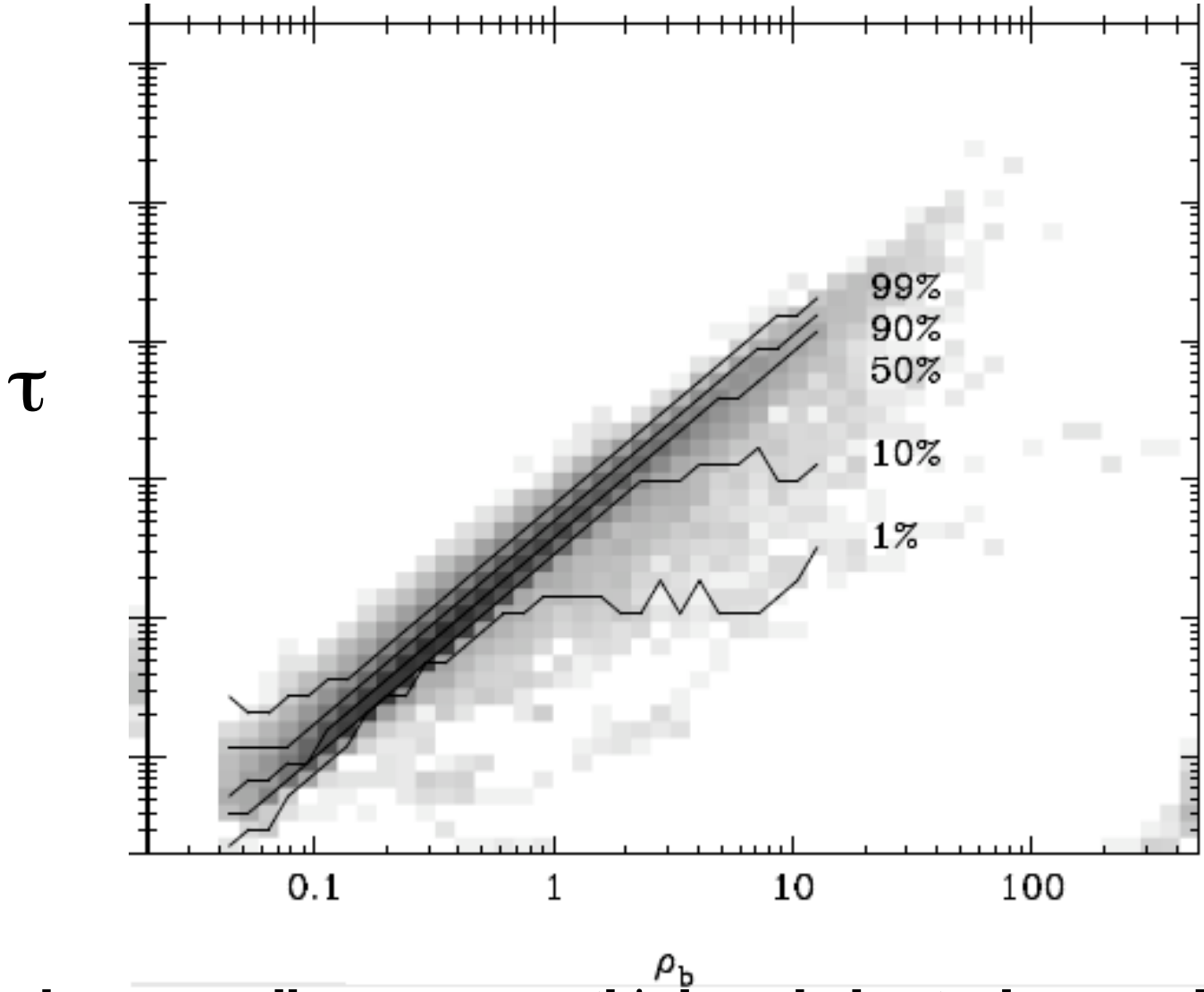
$$F = e^{-\tau}$$

(observable quantity)

Additional physics which could disrupt this simple picture:

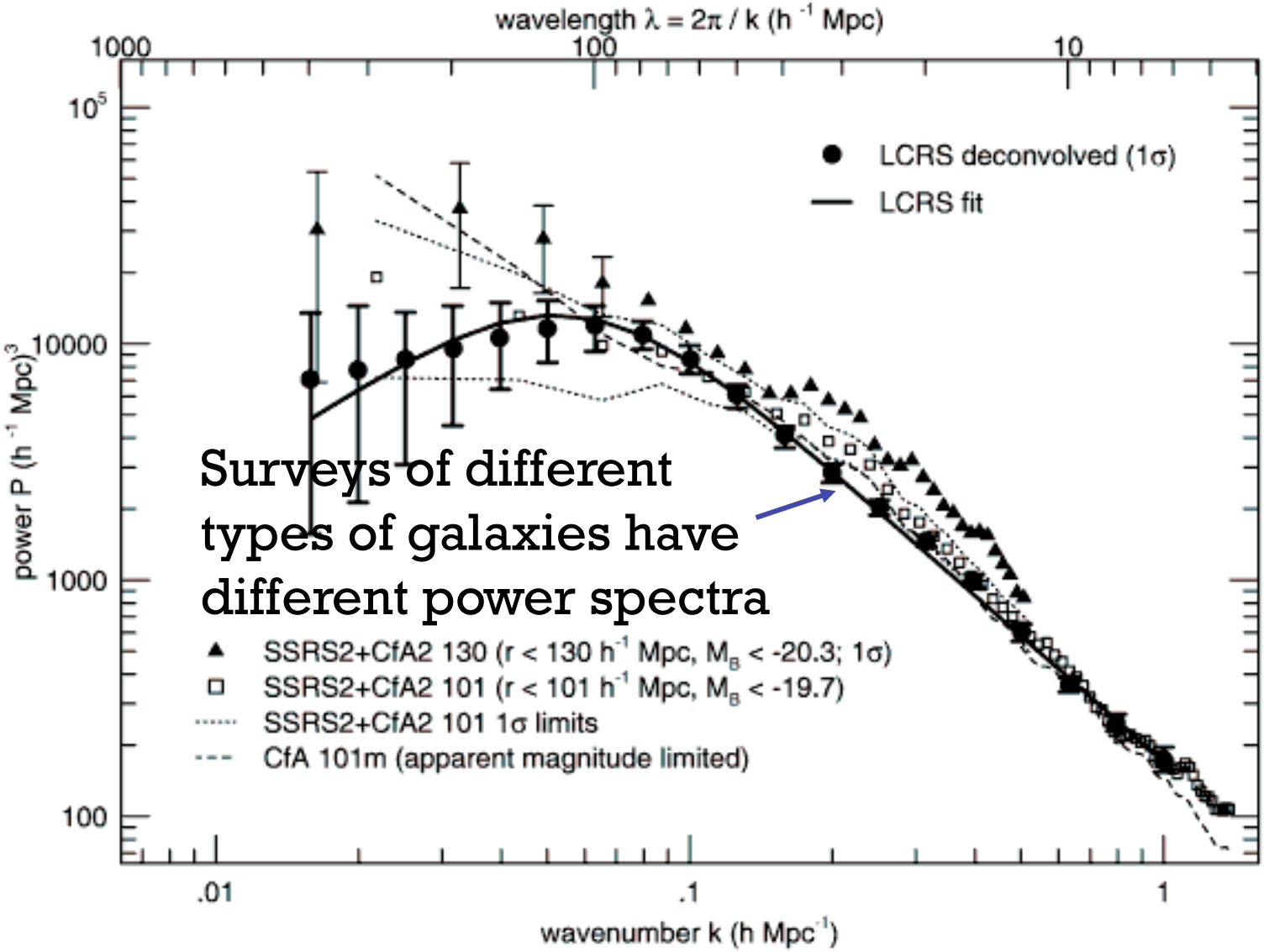
Star formation and supernova winds:

FGPA measured from simulation which includes additional physics (star formation, stellar winds etc)



It works very well - we can use this knowledge to do cosmology

Here is the galaxy power spectrum, but what is the matter power spectrum?



With the Lyα forest we don't have this problem.

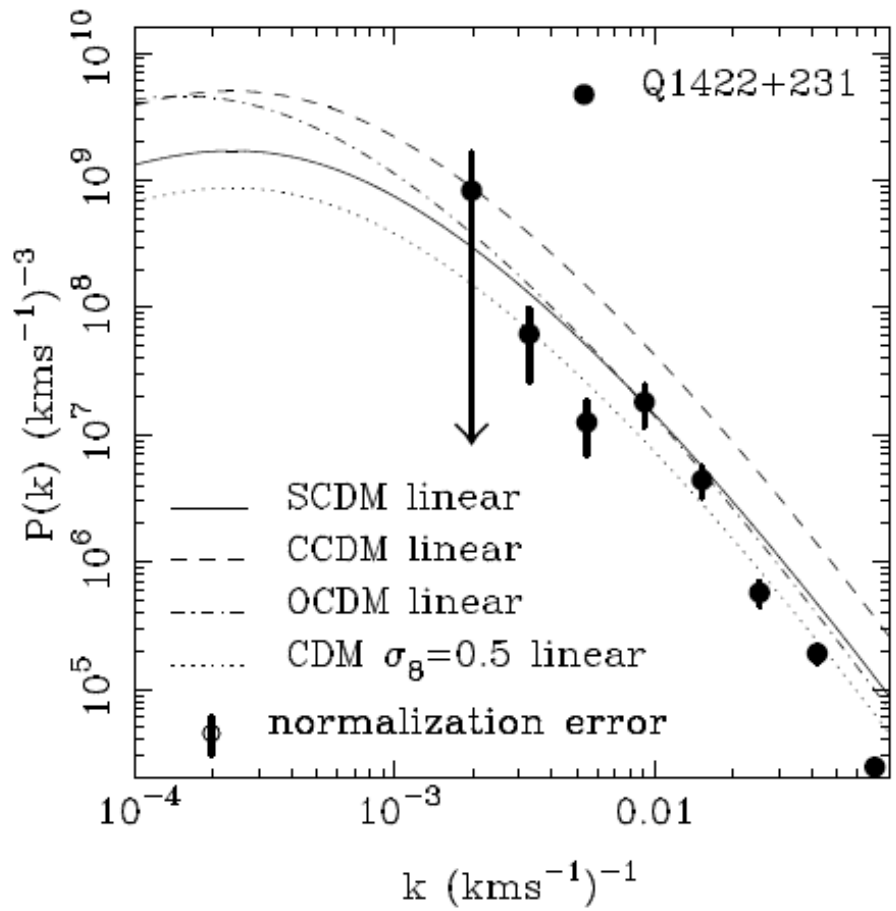
- we know the "biasing relation" for the forest.

- also, the relevant physics is well resolved in simulations (unlike for galaxies).

We can relate clustering of the forest to clustering of matter.

In 1D, we can measure the power spectrum of each quasar spectrum and compare to model predictions

First application, to a single quasar spectrum:
(RC et al, 1998)



Rauch 1998 Annual Reviews

3.5 *Spatial Structure Along the Line of Sight: Clustering and Voids*

Measurements of the two-point correlation function (TPCF) in velocity space along the LOS, $\xi(\Delta v)$, led Sargent et al (1980) to conclude that Lyα clouds are not clustered as strongly as galaxies. Given the probability Δp of finding a pair of clouds with absorption cross section σ and space density $n_0(z)$, separated by a velocity interval Δv, $\xi(\Delta v)$ is given by the following expression:

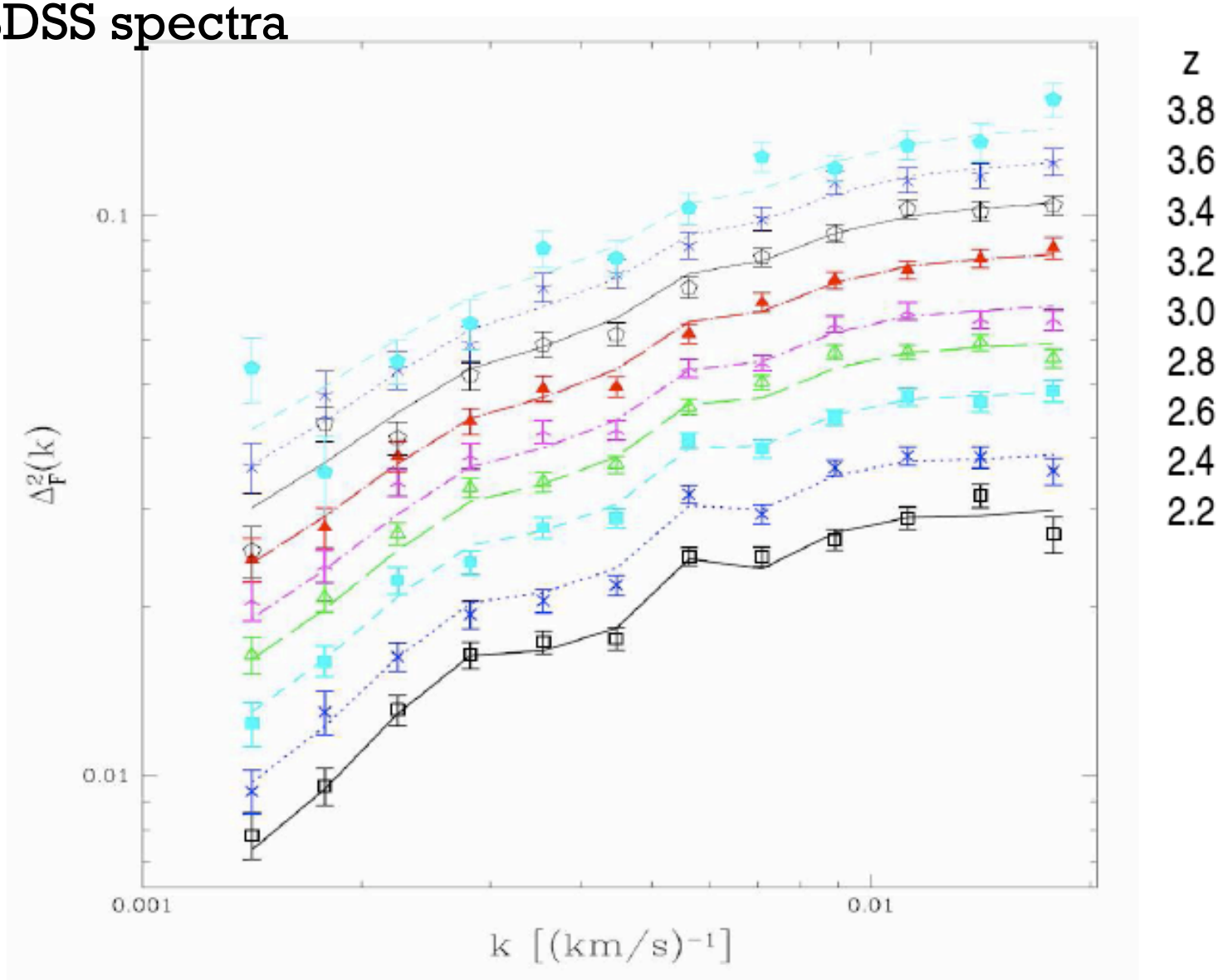
$$\Delta p = n_0 \sigma \Delta v [1 + \xi(\Delta v)], \tag{13}$$

where $\Delta v = c\Delta z/(1+\bar{z})$ is the velocity splitting in the rest frame at mean redshift $\bar{z}$. No correlation signal was found on scales of Δv between 300 and 30,000 km s^{-1}. Clustering for small line pair splittings ($\Delta v \lesssim 300$ km s^{-1}) would still be consistent with this result, given the limited resolution and the effects of blending caused by the large line widths. Based on Voigt profile fits to high resolution data, Webb (1986) obtained the first evidence for the presence of a weak clustering signal [$\xi(100 \text{ km s}^{-1}) \approx 0.5$, at $z \sim 2.5$] at small separations. This result has been confirmed by others (e.g. Muecket & Mueller 1987, Ostriker et al 1988). It is hard to detect the clustering at a high level of significance in any individual QSO spectrum because of the short redshift path length, and both detections and nondetections have been reported (Rauch et al 1992, Kulkarni et al 1996). A variety of techniques seem to indicate, however, that there really is weak clustering in the $z \sim 3$ forest on small scales. If Lyα lines are considered as blends

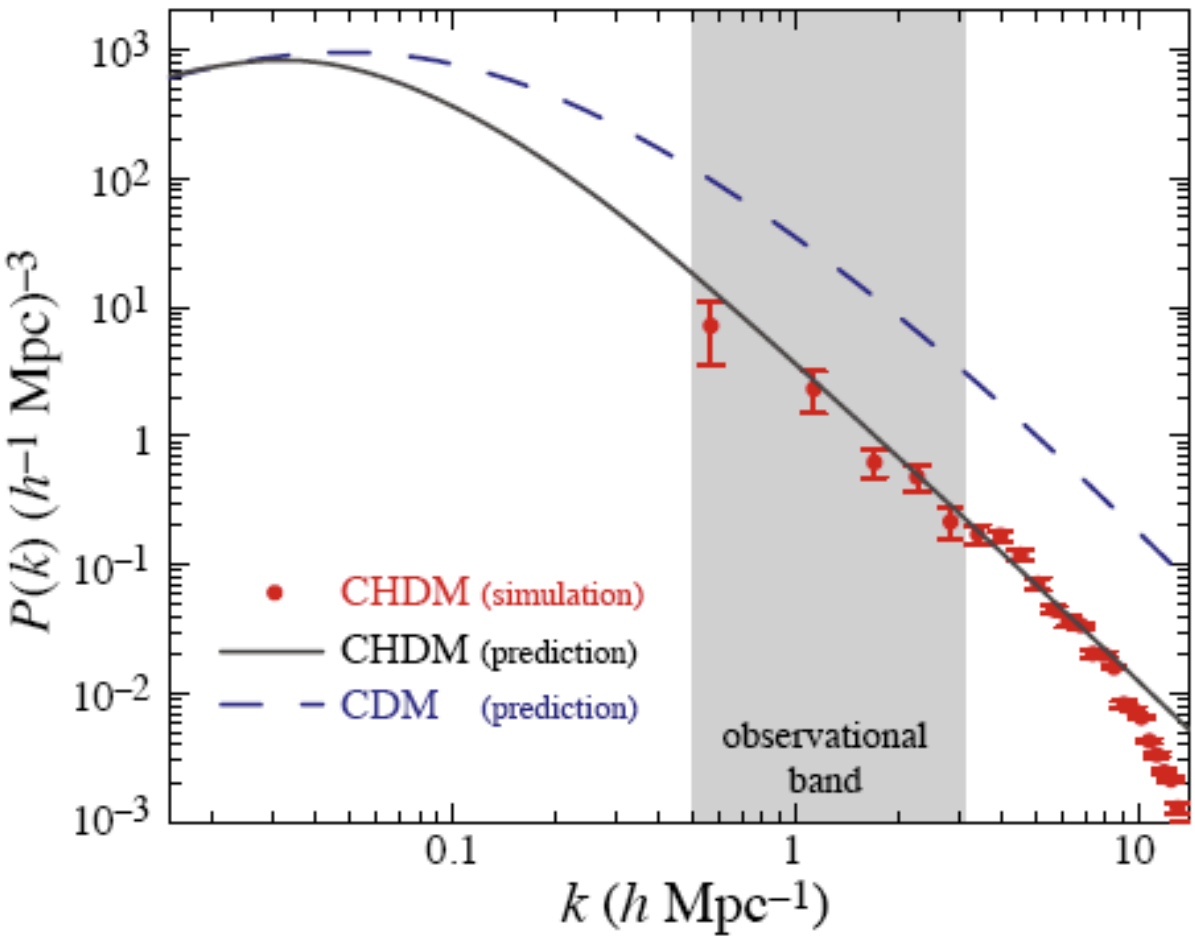
flux power spectrum from

3400 SDSS spectra

McDonald et al (2006)



P(k) suppression by neutrinos



A simulation test which included massive neutrino particles (10 eV)

(RC, Hu and Dave' (1999))

Current observational constraints are < 1 eV

Can also constrain warm dark matter:

Limits from
Viel et al (2007)
$m_{WDM} > 8$ keV

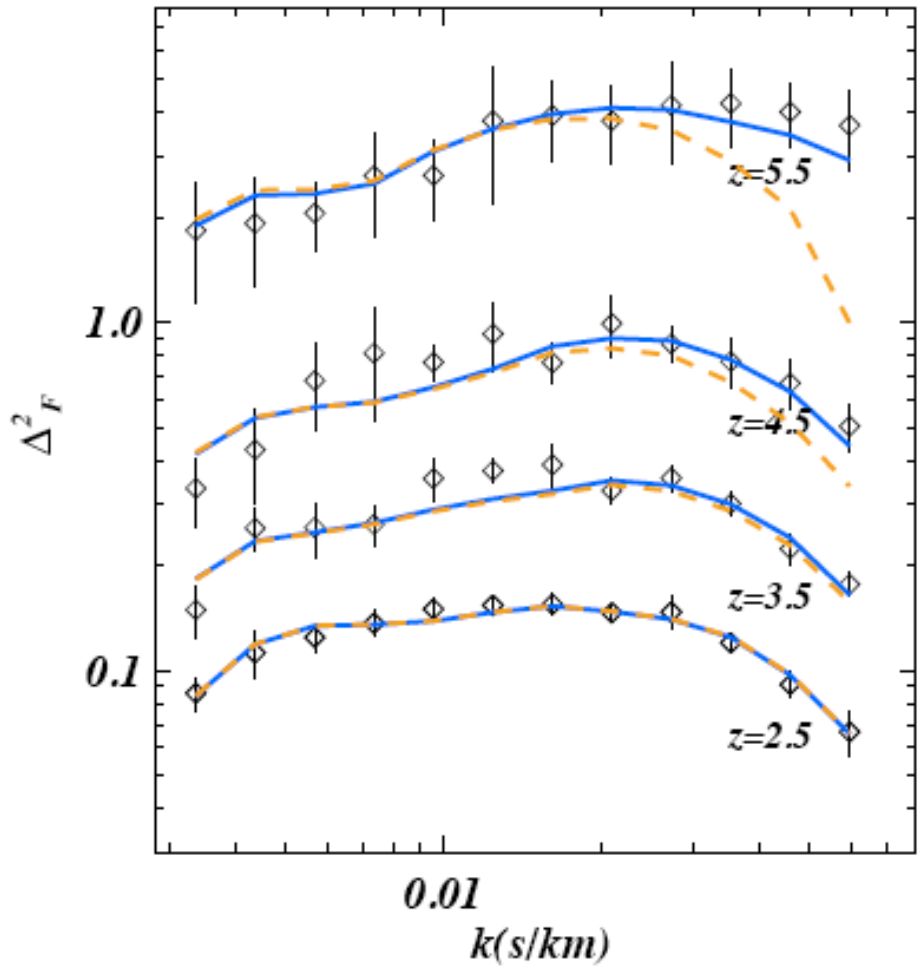


FIG. 1: Flux power spectrum of the HIRES data set at different redshifts and best fit models (solid curve) with $m_{\rm WDM} = 8$ keV and a model with $m_{\rm WDM} = 2.5$ keV (dashed curve).

Inflationary parameters, like the scalar spectral index and the roll:

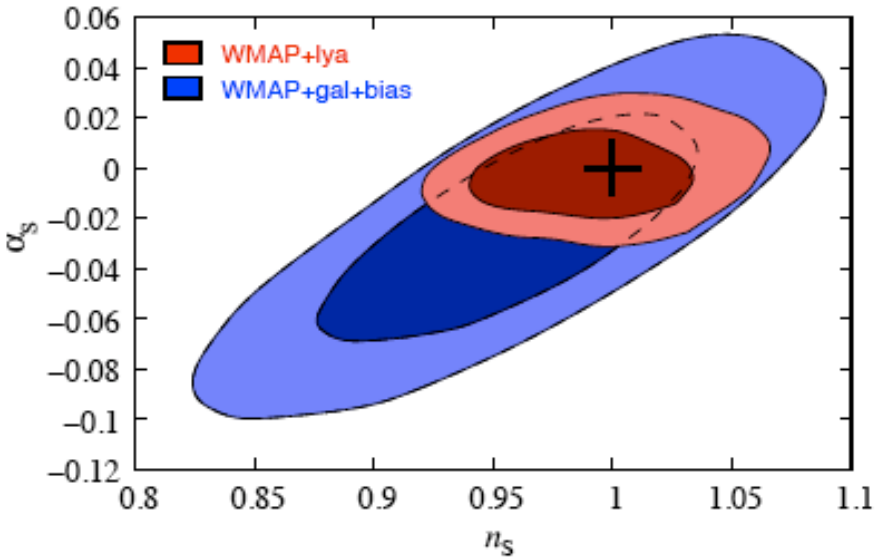


FIG. 3: 68% (inner, dark) and 95% (outer, light) contours in the (α_s, n_s) plane using WMAP+SDSS-lya versus WMAP+SDSS-gal+bias. Adding the SDSS Lyα forest dramatically reduces the allowed region of parameter space in this plane. Note that the simplest model with $n_s = 1$ and $\alpha_s = 0$ is within 68% interval.

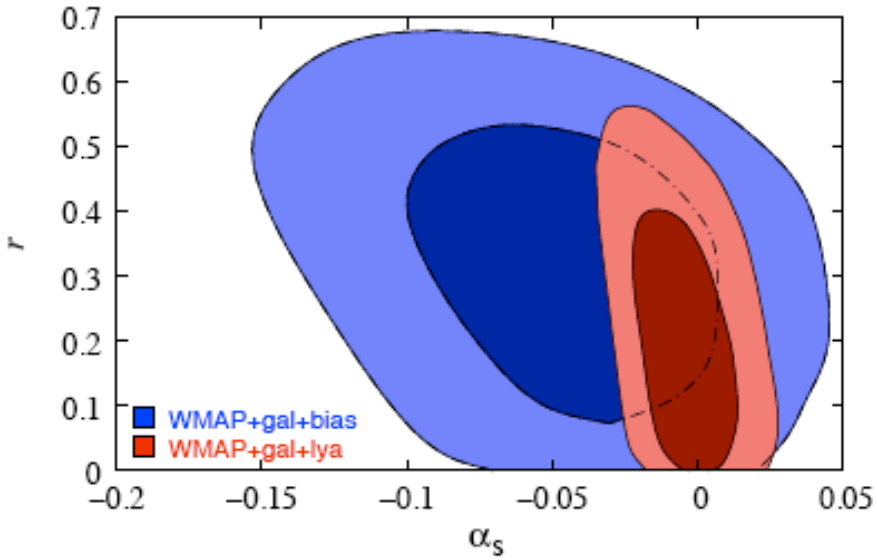


FIG. 4: 68% (inner, dark) and 95% (outer, light) contours in the (α_s, r) plane using WMAP+SDSS-lya versus WMAP+SDSS-gal+bias. Adding the SDSS Lyα forest dramatically reduces the allowed region of parameter space in this plane. Note that the simplest model with $\alpha_s = 0$ and $r = 0$ is within the 68% interval.

From Seljak et al (2005)

Sloan Digital Sky Survey III

Mapping the distant universe

BOSS: Dark Energy and the Geometry of Space

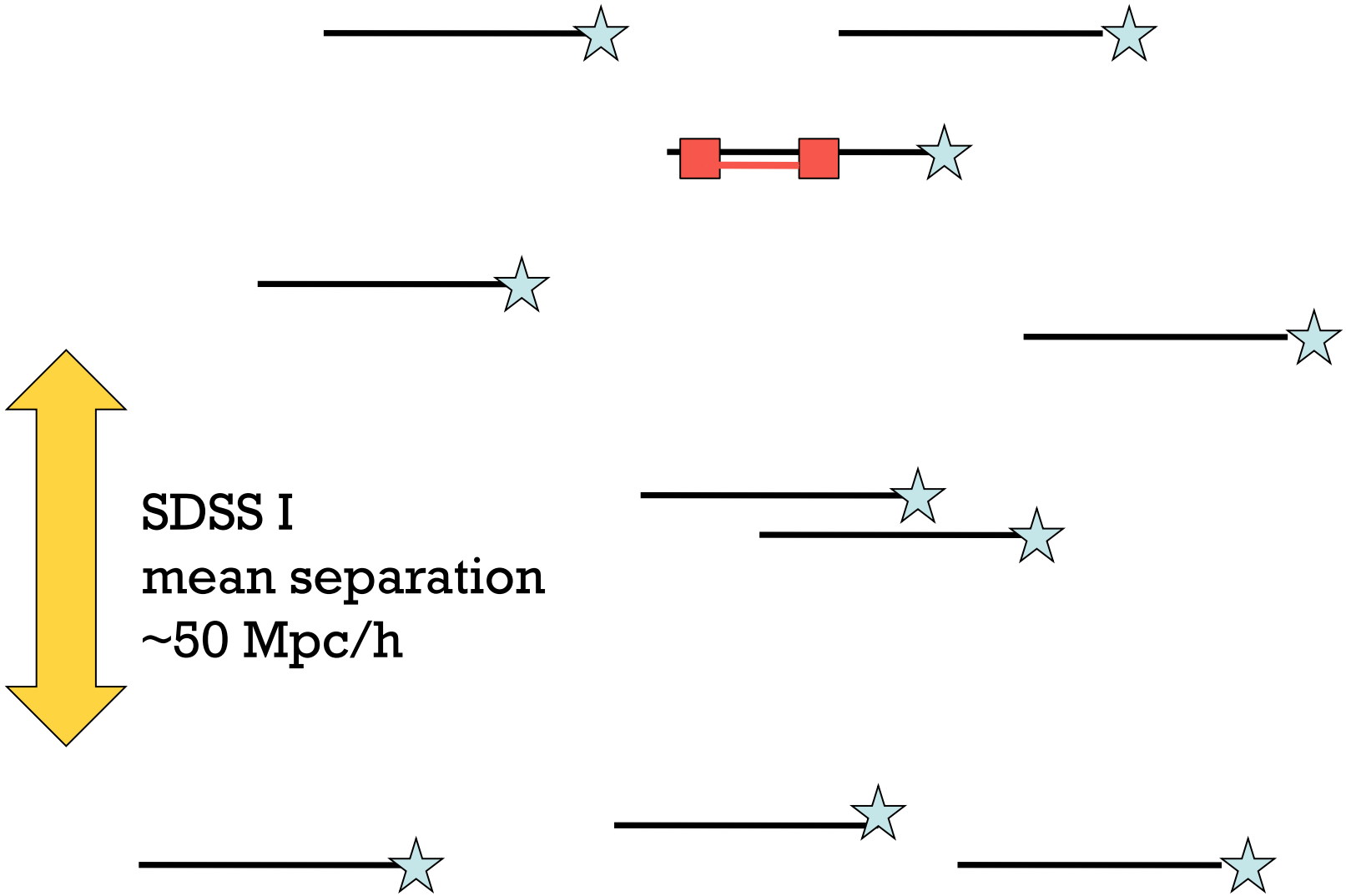
The SDSS-III's Baryon Oscillation Spectroscopic Survey (BOSS) will map the spatial distribution of luminous galaxies and quasars to detect the characteristic scale imprinted by baryon acoustic oscillations in the early universe. Sound waves that propagate in the early universe, like spreading ripples in a pond, imprint a characteristic scale on cosmic microwave background fluctuations. These fluctuations have evolved into today's walls and voids of galaxies, meaning this baryon acoustic oscillation scale is visible among galaxies today.

A survey
with a huge volume
and many spectra…

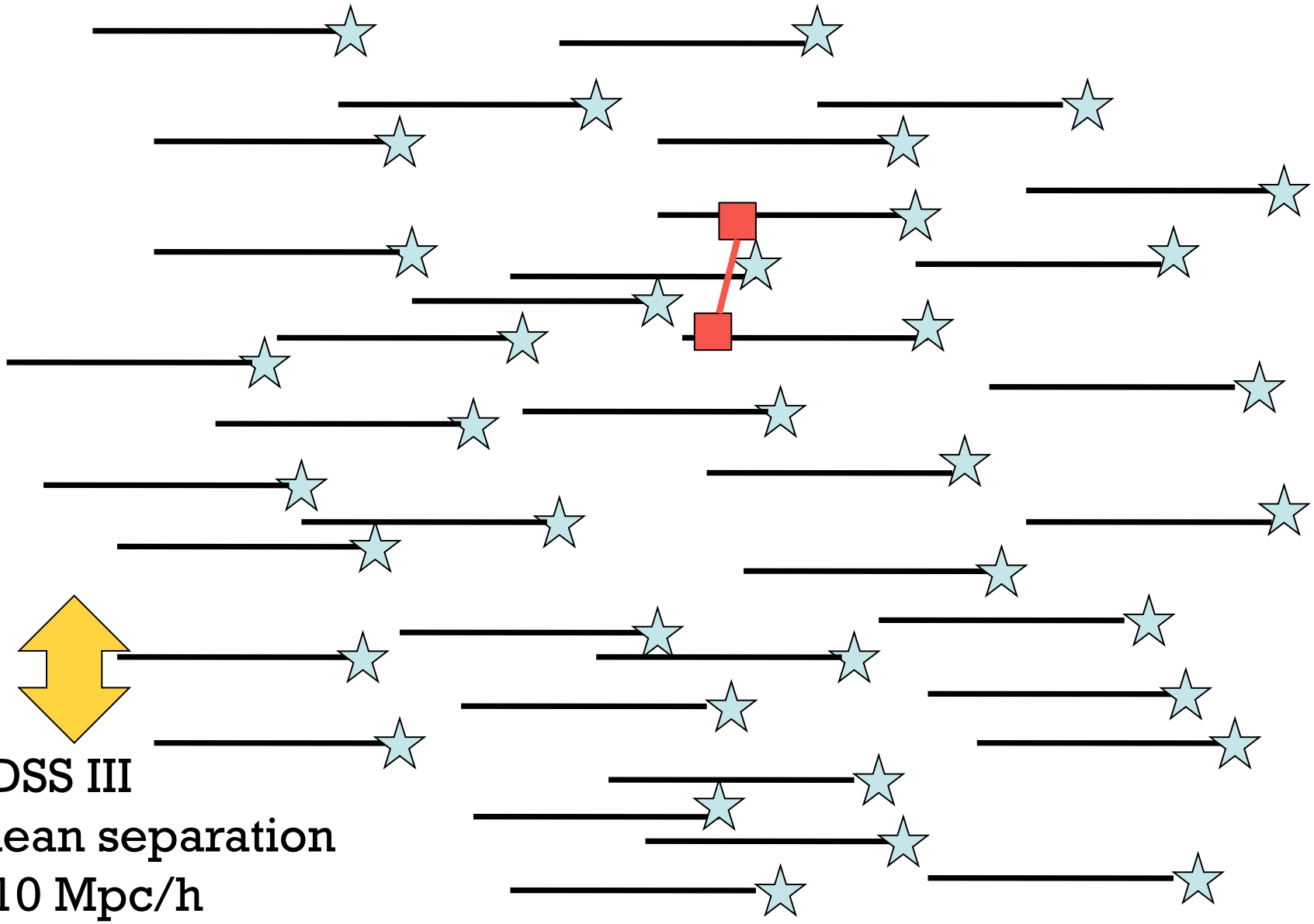
BOSS at a glance

- Dark time observations
- Fall 2009 - Spring 2014
- 1,000-fiber spectrograph, resolution R~2000
- wavelengths 360-1000 nm
- 10,000 square degrees
- Redshifts of 1.5 million luminous galaxies to $z = 0.7$
- Lyman-α forest spectra of 160,000 quasars at redshifts $2.2 < z < 3$

pre-2011 1D clustering

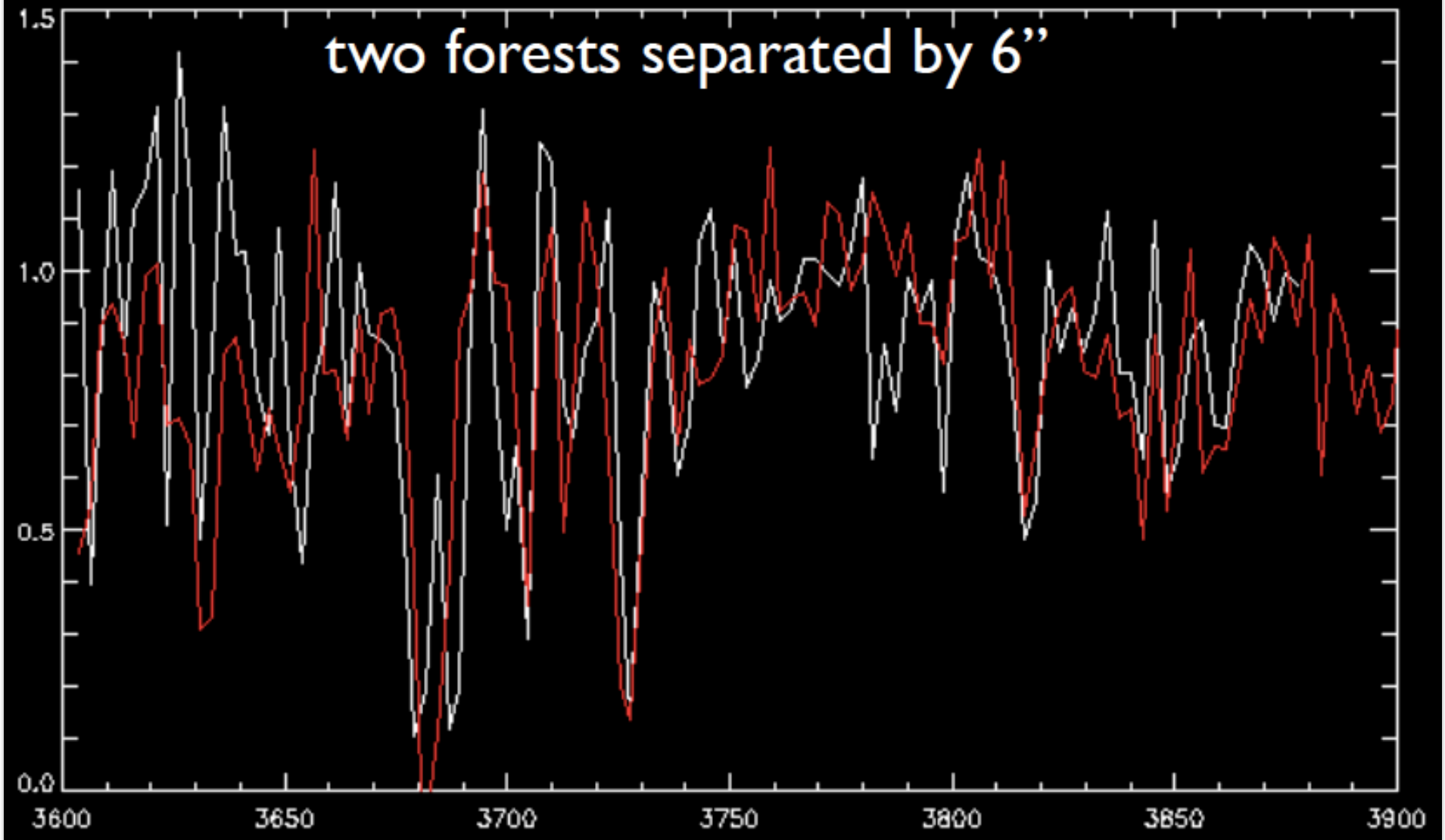


2011+ 3D clustering



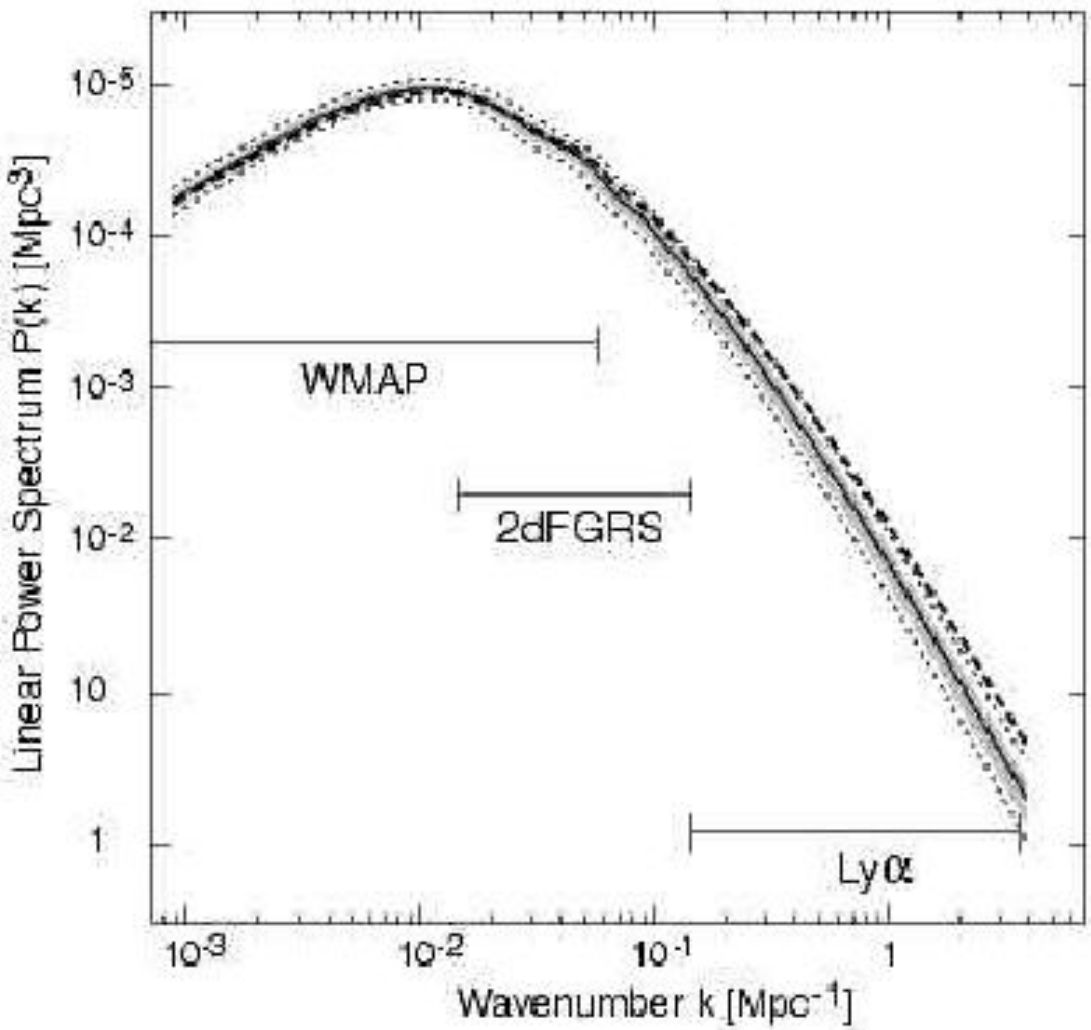
SDSS III
mean separation
~10 Mpc/h

Cross-correlation between sightlines – 3D information



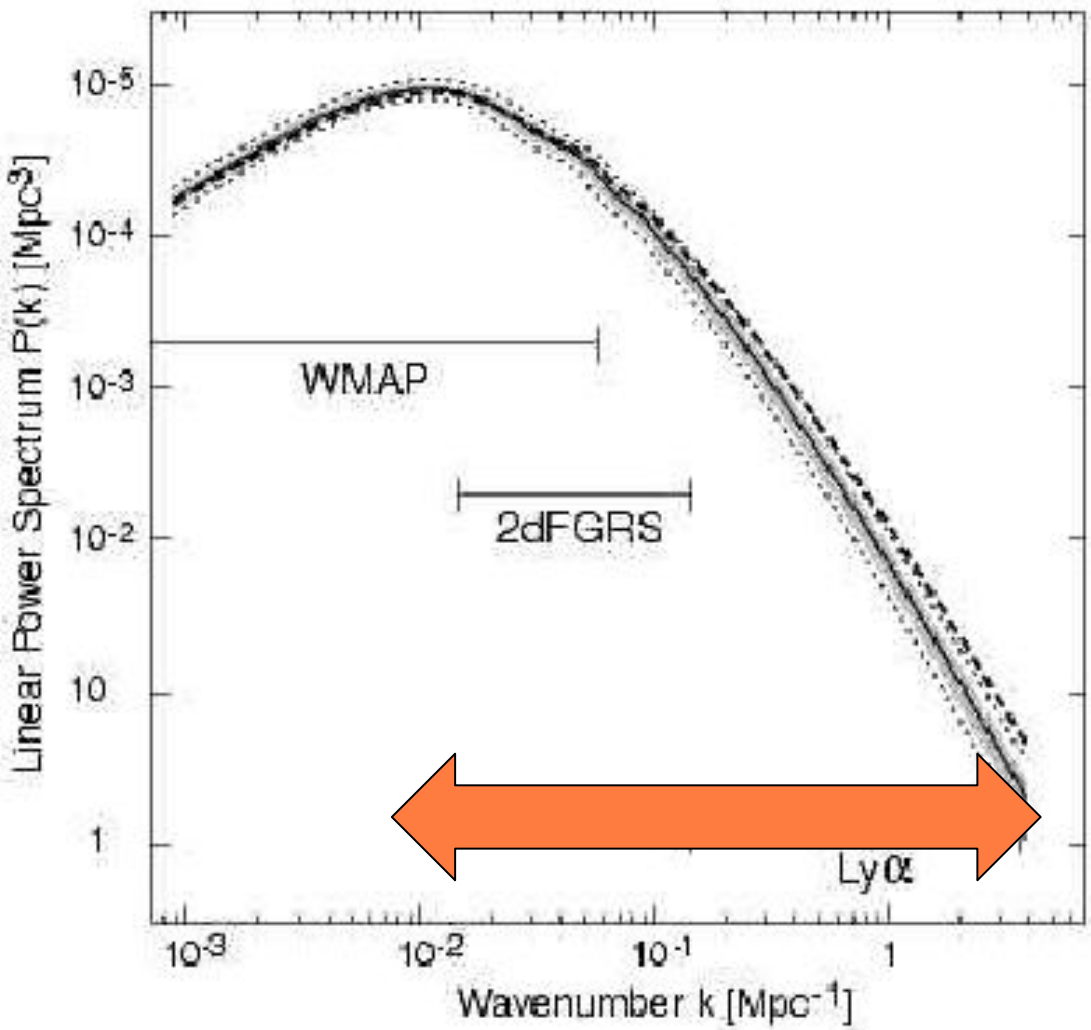
Nicolas Busca

Not just for small scales any more…

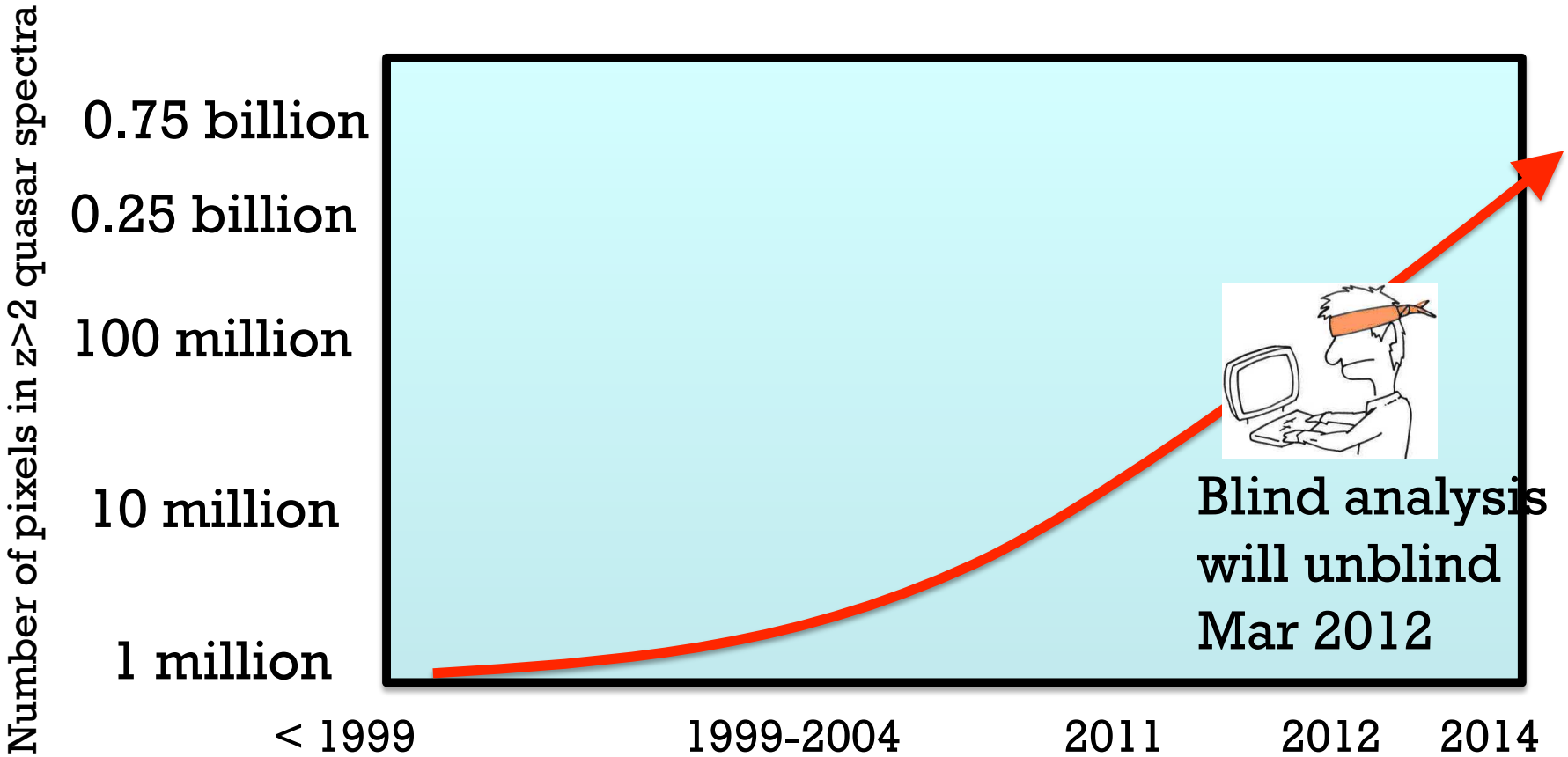


Spergel
et al (2003)

Not just for small scales any more…



Number of pixels vs time for Ly α forest clustering…



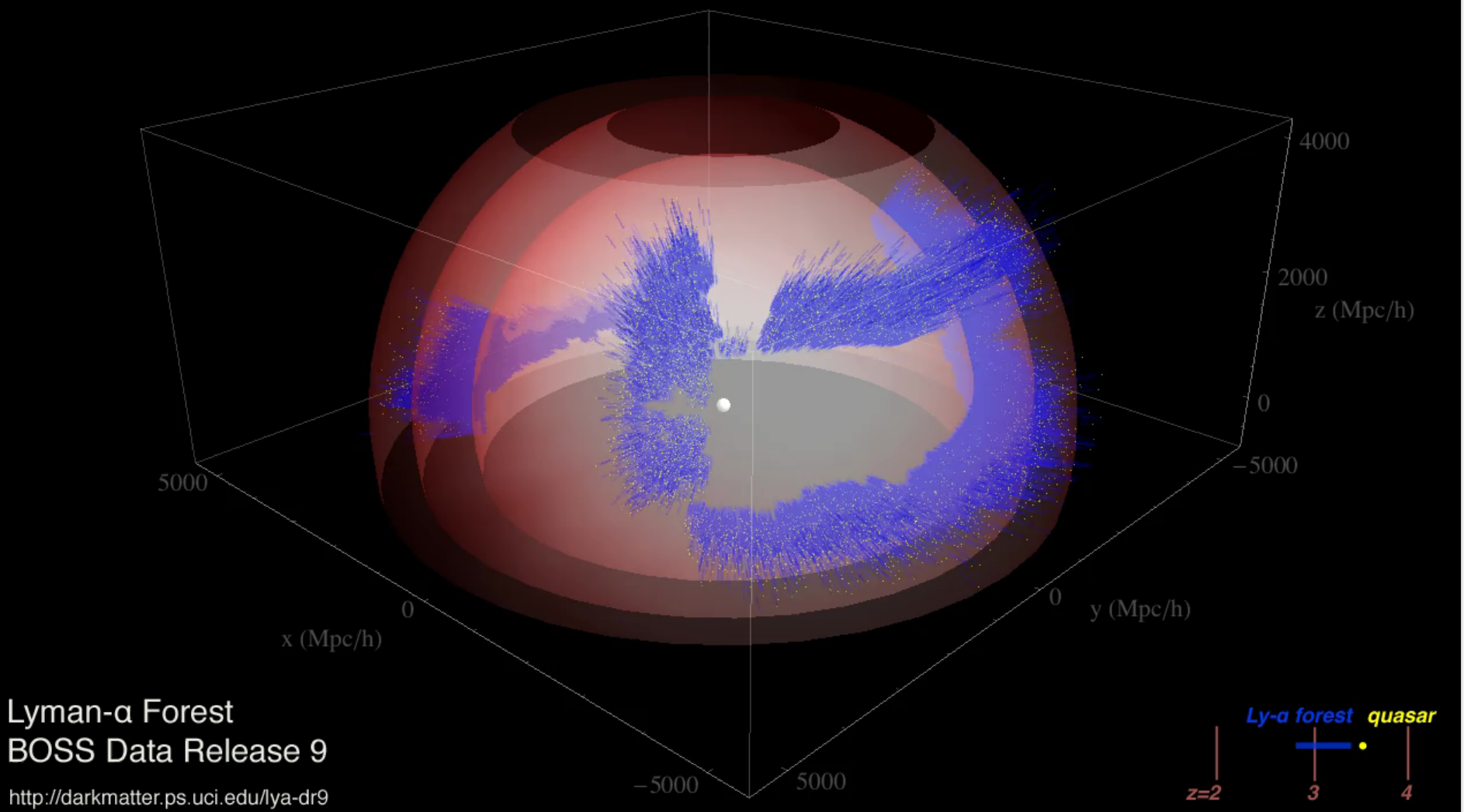
No clustering detected beyond ~1 Mpc/h

1D clustering Measured up to ~20 Mpc/h scales

3D clustering measured up to ~100 Mpc/h scales

BAO scale 3D clustering

3D distribution of Ly α forest pixels



David Kirkby

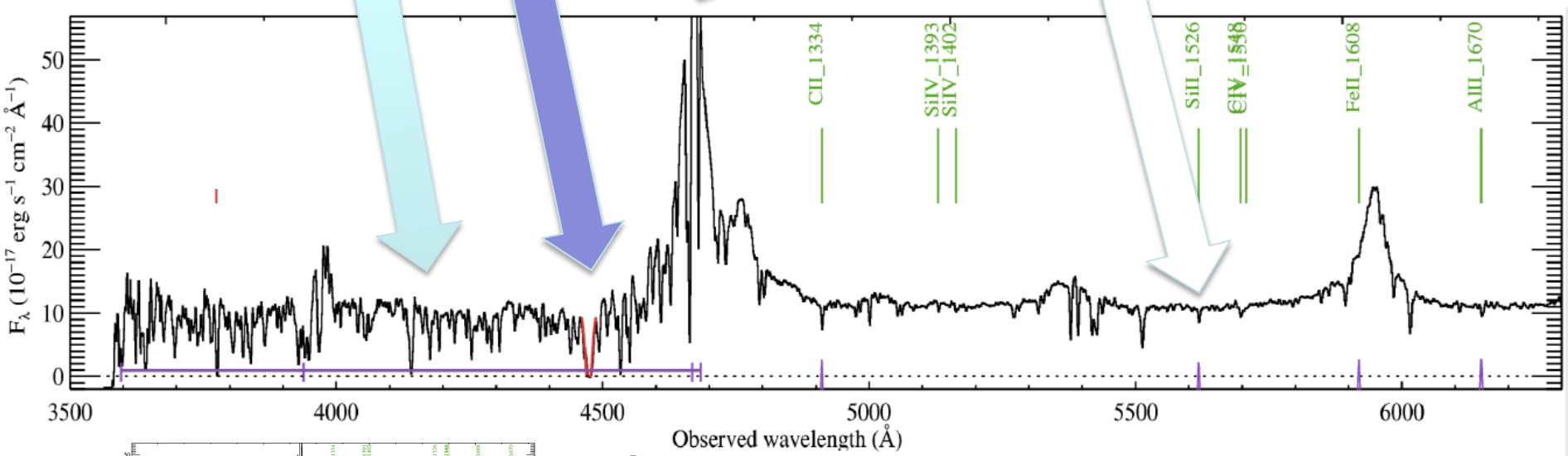
Not just a redshift…

Ly α forest

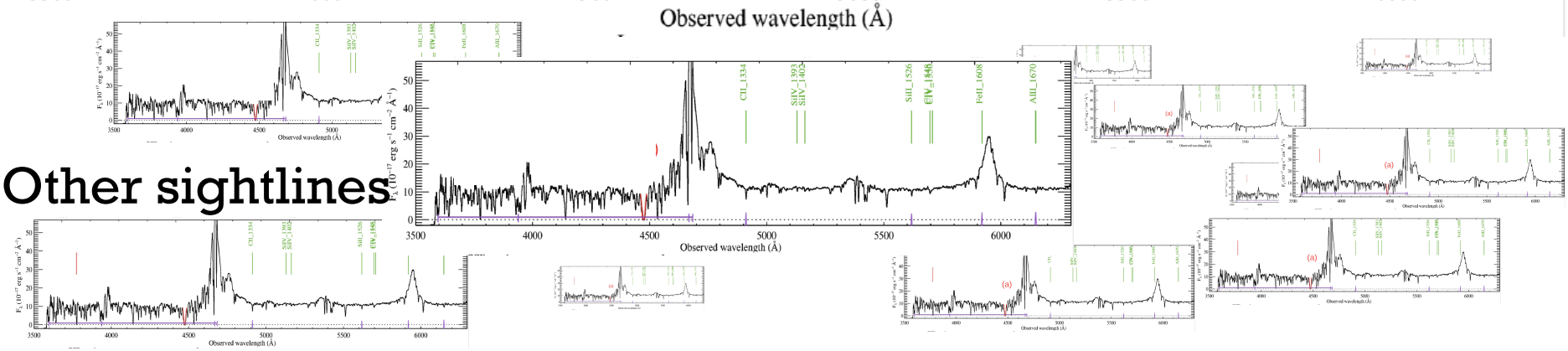
Damped Ly α

Quasar Ly α emission

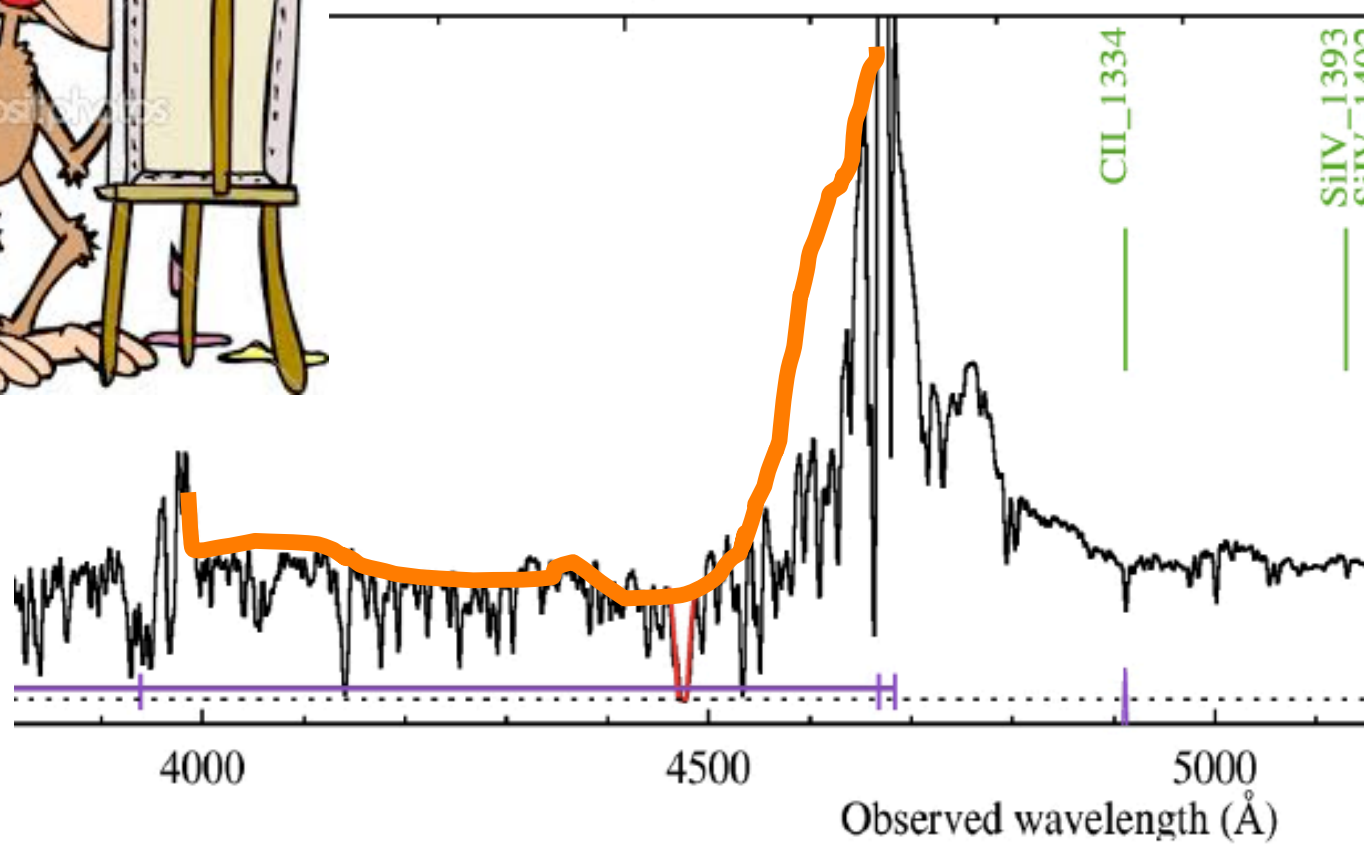
Metal line



Other sightlines

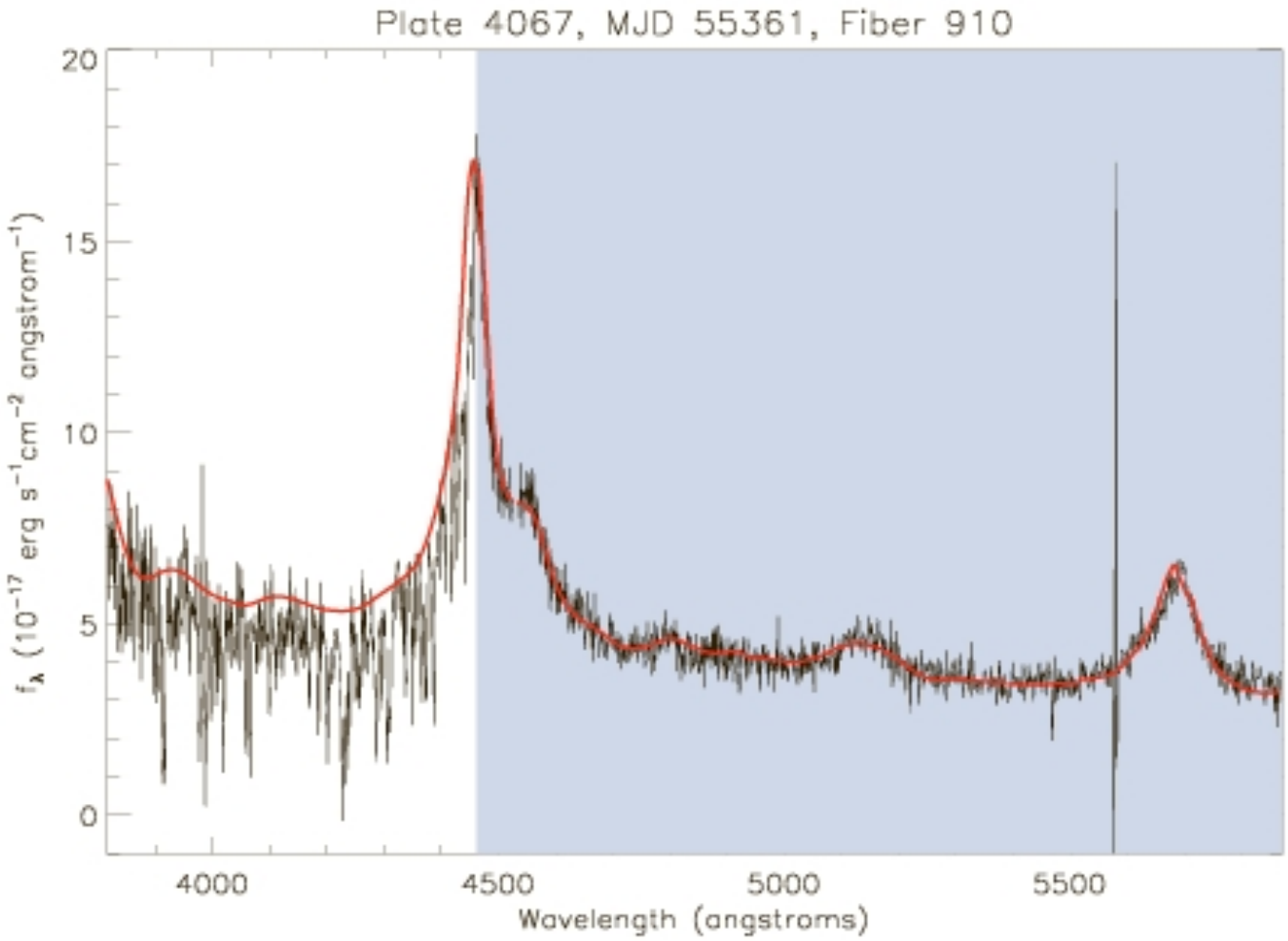


Continuum fitting…



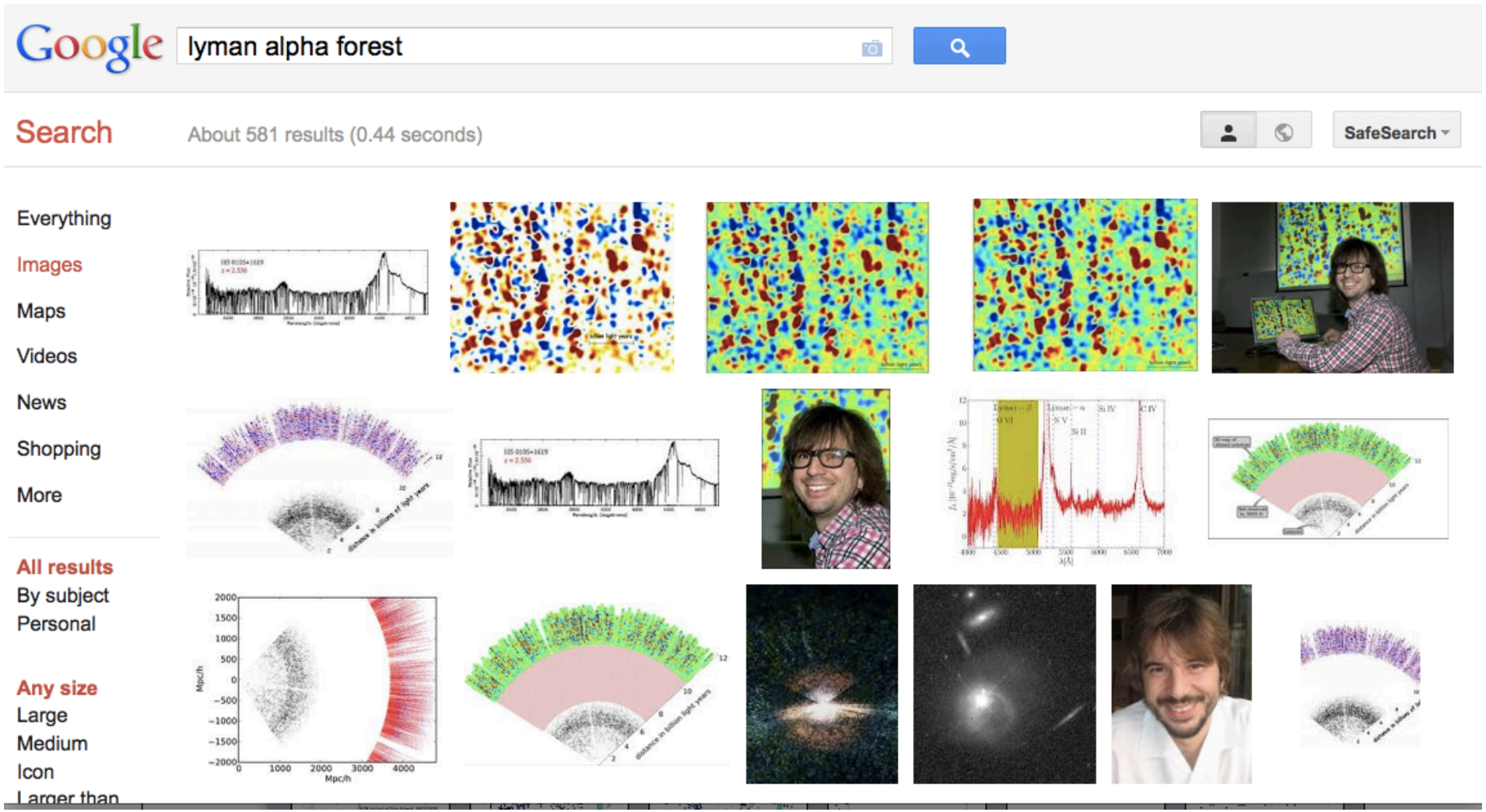
Principal component continuum fitting

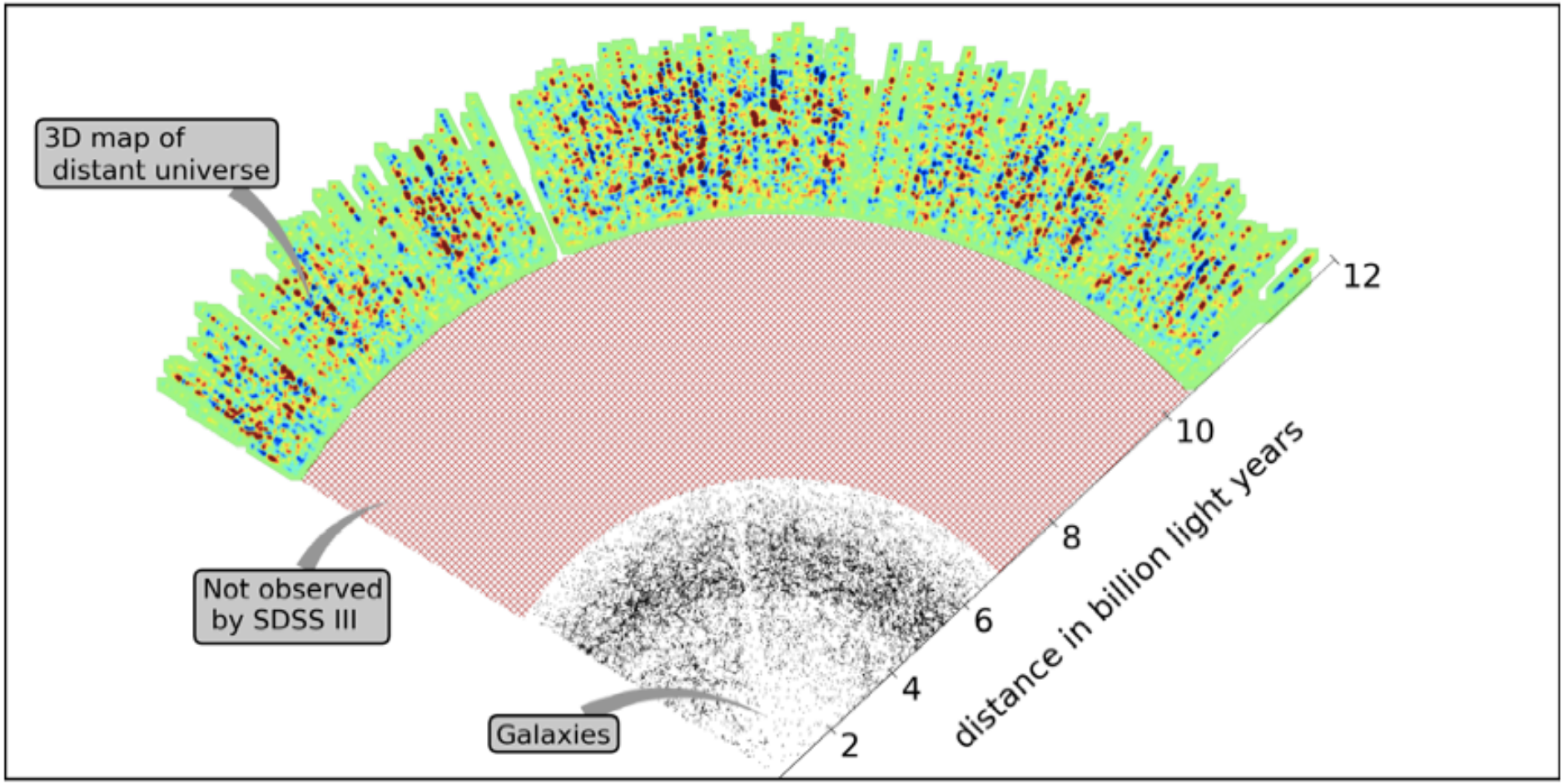
5% error
for S/N=5



K.G. Lee, Nao Suzuki

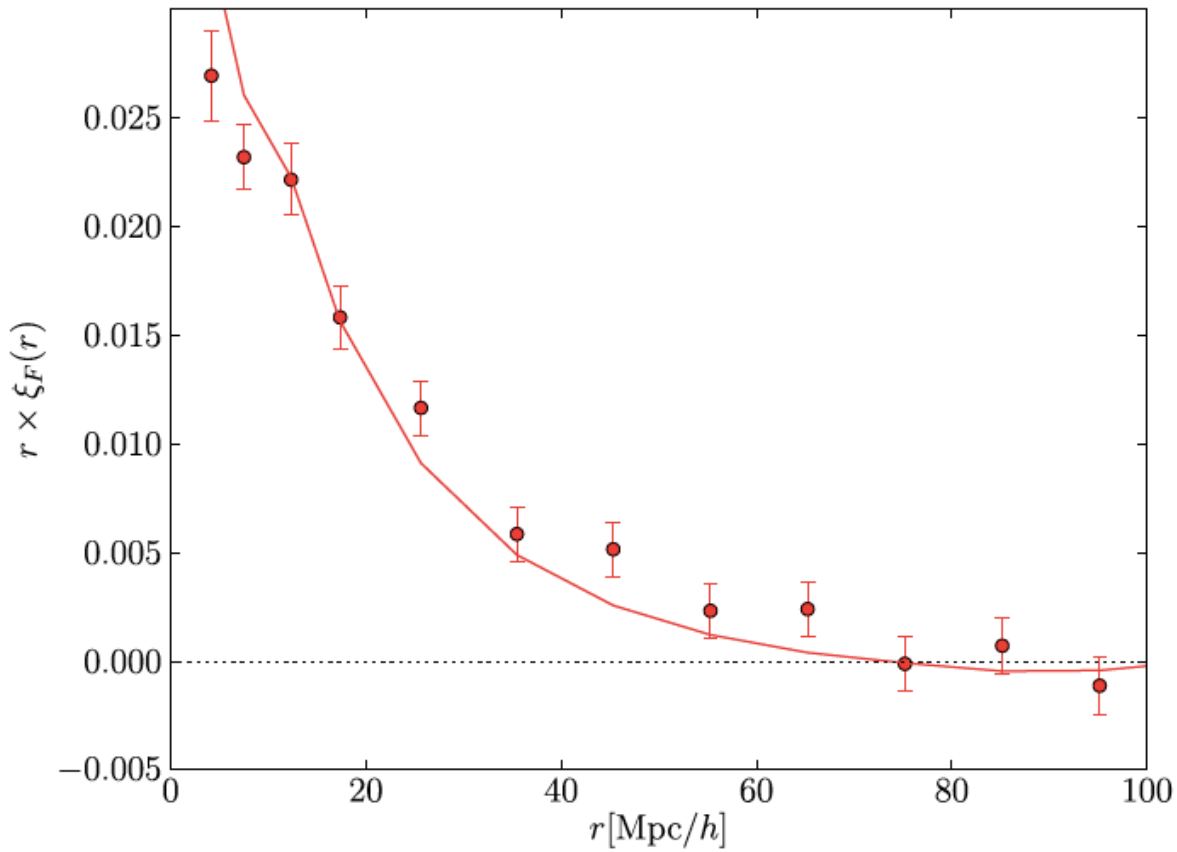
First measurement of 3D clustering on large scales, Slosar et al. 2011 (arxiv1104.5244)




3D map of
distant universe
Not observed
by SDSS III
Galaxies
2
4
6
8
10
12
distance in billion light years

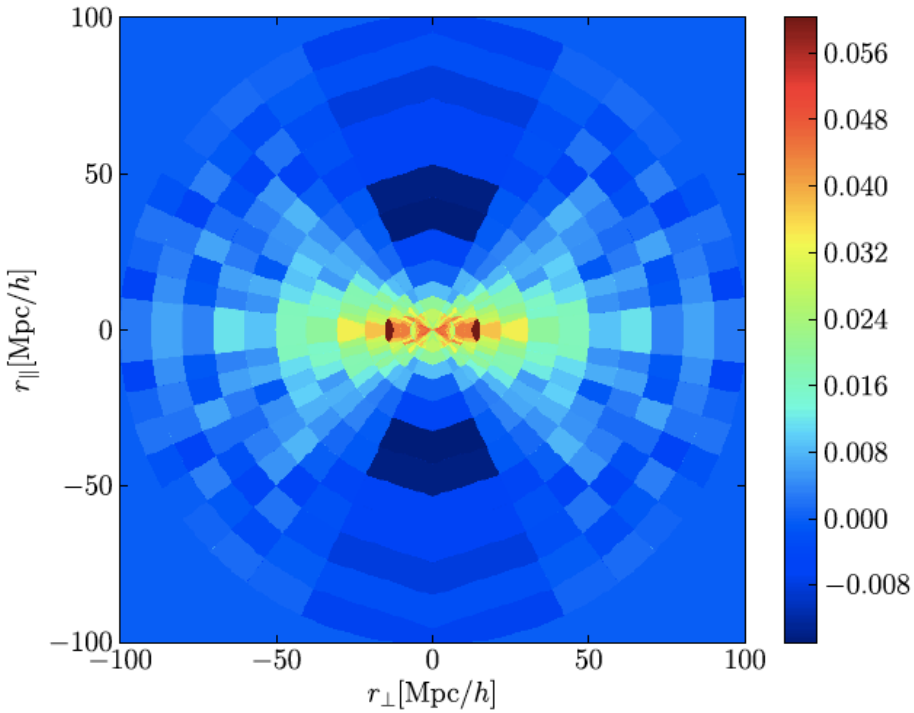
First measurement of 3D clustering on large scales, Slosar et al. 2011 (arxiv1104.5244)

(SDSS3's first "first"?)

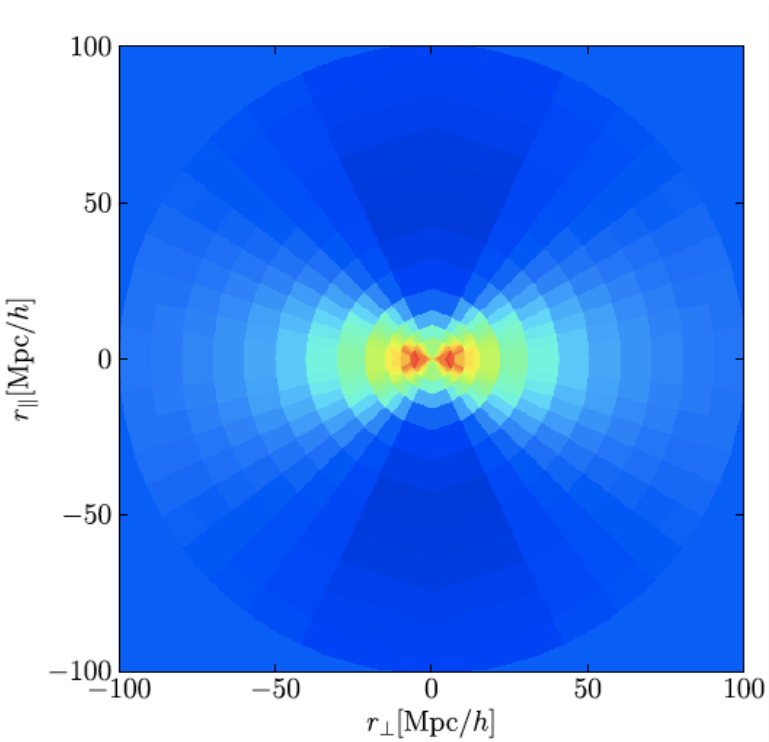


(from 10,000 quasar Spectra)

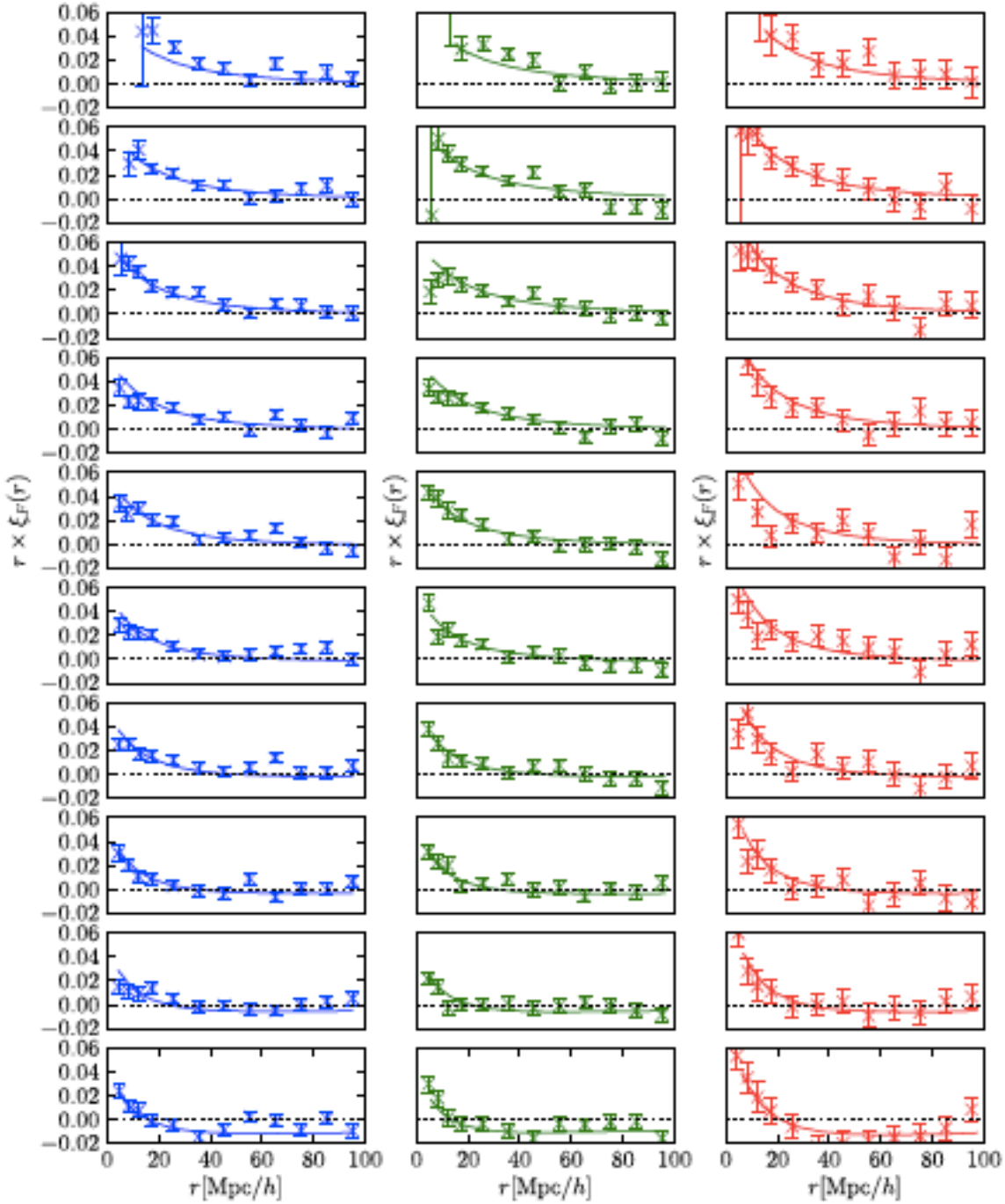
Redshift distortions

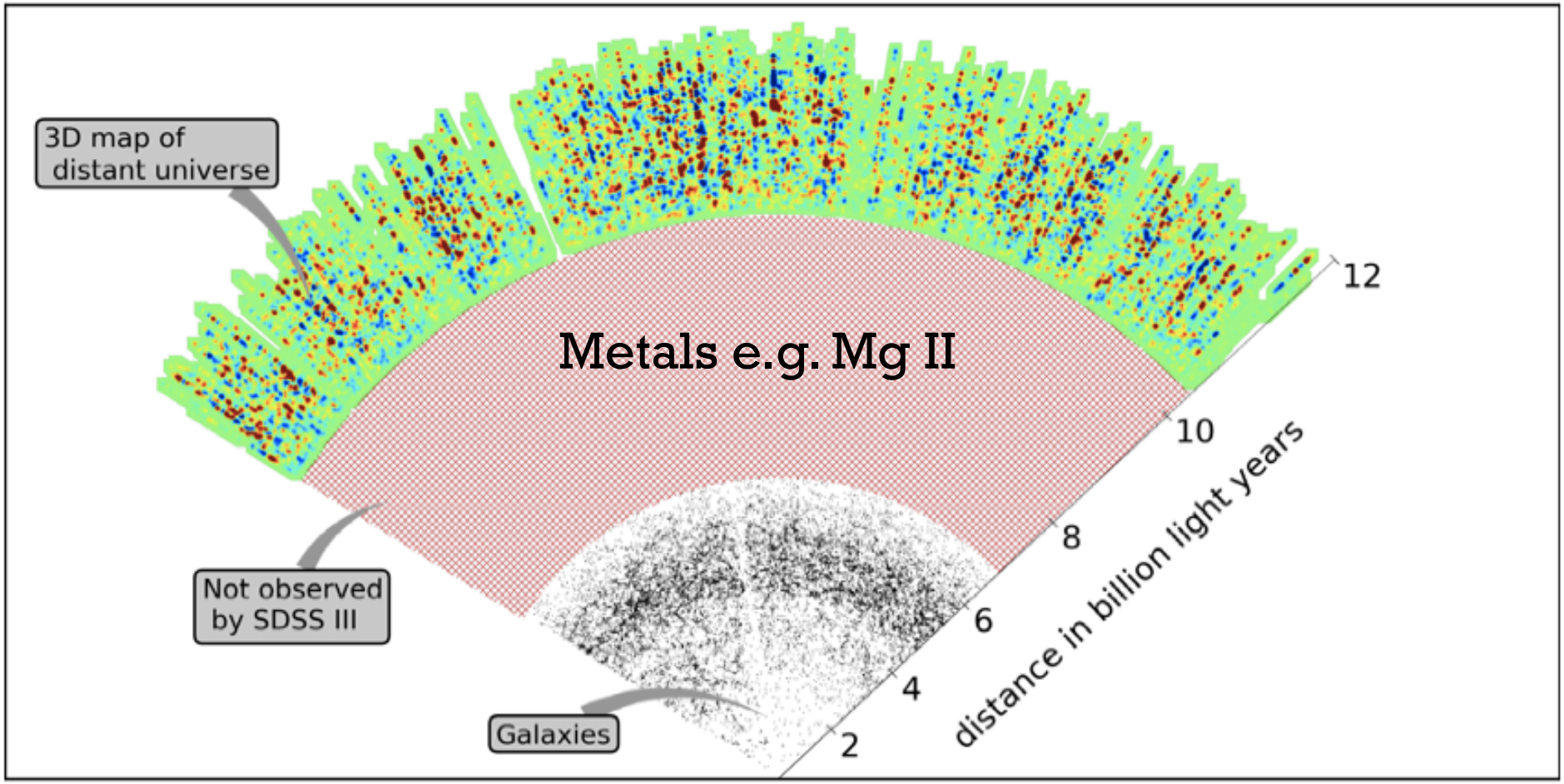


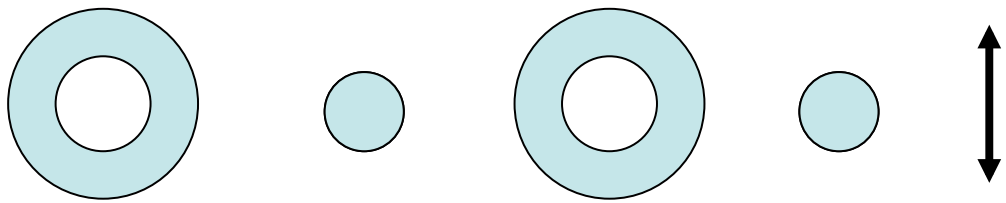
BOSS



LCDM

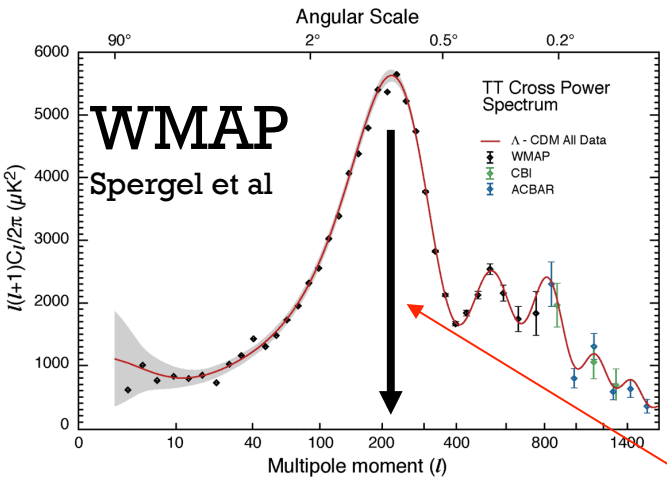

$r \times \xi_F(r)$
r[Mpc/h]
0.06
0.04
0.02
0.00
−0.02
0
20
40
60
80
100


3D map of
distant universe
Metals e.g. Mg II
Not observed
by SDSS III
Galaxies
2
4
6
8
10
12
distance in billion light years



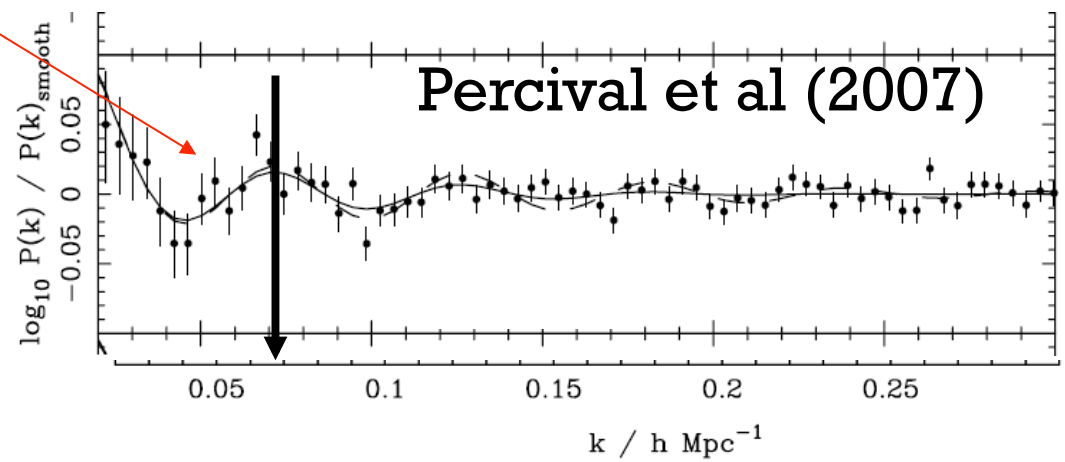
size of the
sound horizon
at matter-radiation
equality

Baryon acoustic oscillations make a standard ruler



CMB z~1100

SDSS Galaxies z~0.3



The Lyman alpha forest does this at z~3

The post 2014 future:

BigBOSS

10 times more spectra

Conclusions:

- The Lyman alpha forest arises in a fluctuating photoionized intergalactic medium, not from gravitationally collapsed objects.

- Understanding this simple physics means that it provide a maps of the density field.

- This can be used to do cosmology, from constraints on the neutrino mass to dark energy from BAO.

0.25 billion pixels of 3D LSS information will become public in July 2012 (SDSS DR9)